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Energy-Efficiency Standards for Consumer Durables: Investment Decisions, Rebound Effects, and Distributional Consequences

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February 4, 2025

Abstract

We analyze energy-efficiency policy in the form of a minimum-efficiency standard for consumer durables such as cars, building insulation, or household appliances. Such a policy has two effects. At the intensive margin, a household that invests will choose a more efficient device. At the extensive margin, more households will choose not to invest at all. We analyze the equilibrium effects of a minimum-efficiency standard, taking household heterogeneity, endogenous investment decisions, and price adjustments into account. A moderate minimum-efficiency standard increases demand for more efficient consumer durables and reduces energy demand. A stricter policy is less effective or even counterproductive.

In particular, we show that a stricter minimum-efficiency standard increases the rebound effect and ultimately backfires. We decompose the rebound effect and uncover a new channel arising from the endogenous investment decisions. In our central calibration of the CAFE standard, this investment effect accounts for one third of the total rebound effect and makes a stricter standard almost ineffective. Finally, we analyze the distributional consequences of a minimum-efficiency standard and compare them to those of an energy tax. Producers of household appliances (“energy-efficiency capital”) benefit more and energy producers suffer more from the standard than from the tax. Furthermore, non-investing households prefer the standard, whereas investing households tend to prefer the tax.

JEL Codes: D15 · D61 · Q41 · Q48

Keywords: Energy Efficiency · Extensive Margin · Gruenspecht Effect · Household Heterogeneity · Investment · Rebound Effect · Theory of Environmental Policy

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1 Introduction

Households make up a large share of total fuel and electricity consumption. A widespread, and seemingly natural, way to increase energy efficiency and thereby reduce energy consumption is to introduce minimum-efficiency standards for consumer durables. For instance, the European Union has banned the sale of light sources, vacuum cleaners or other electronic products if they consume too much electricity (European Commission, 2025).¹ Similar regulations aim at cars, space-heating systems, building insulation or household appliances.²

Do these policies actually reduce aggregate energy consumption? To answer this question, we need to look at the policy goal. For any given energy service (such as lighting), energy efficiency is usually a fixed characteristic of a device (such as a light bulb). To increase energy efficiency of the energy service, the household usually has to scrap and replace the existing device. At any given time, there are some households that are planning such an investment because their old devices are too inefficient. Energy efficiency policy targets these households, because the decision to invest is voluntary, and minimum-efficiency standards usually apply only to new devices, not to existing ones. Therefore, tightening a binding standard has two opposite effects. At the intensive margin, it will increase the energy efficiency of all households that still invest. At the extensive margin, fewer households may decide to invest at all and instead keep their old devices. Thus, a minimum-efficiency standard will increase overall energy efficiency and reduce aggregate energy consumption only if the first effect dominates.

To determine under which conditions this is the case, this article analyzes the equilibrium effects of minimum-efficiency standards. We model two interdependent markets: firstly, the market for energy, which can represent fuel or electricity, and secondly, the market for “household energy-efficiency capital”, i.e. the energy efficiency embodied in consumer durables. If a household has a larger amount of capital, a given amount of energy will be converted into more energy services. Households are heterogeneous with respect to their capital endowment, i.e. their *initial* energy efficiency. Without a minimum-efficiency standard, households are free to choose how much energy-efficiency capital they buy. This implies a cutoff level of capital below which households invest; those with more keep their endowment. Introducing a binding minimum-efficiency standard increases the amount of capital that investing households (have to) choose, but it also lowers the cutoff level, which reduces the share of investing households. Additionally, the cutoff level reacts to price changes: if the standard increases capital demand and decreases energy demand, both the capital price increase and the energy price decrease will lower the cutoff.

The main contributions of this article are as follows. Firstly, it shows how introducing a minimum-efficiency standard changes the cutoff level. Without such a standard, the investing households balance capital and energy expenditures to minimize the cost of energy services.

¹For analyses of the European Union’s light-bulb regulation, see Frondel and Lohmann (2011) or Perino and Pioch (2017).

²The 2022 *International Energy Efficiency Scorecard* (Subramanian et al., 2022) by the American Council for an Energy-Efficient Economy (ACEEE), a nonprofit research organization, approvingly lists several direct intervention policies and gives an overview of their implementation in 25 countries.

A *weak* standard – that is, one that barely binds – does not change this expenditure balance, but a *strong* standard – that is, one that strictly binds – forces the investing households to pay too much for capital relative to energy, which discourages them from investing. We show that the elasticity of the cutoff level with respect to the standard is proportional to the enforced difference between capital and energy expenditures. The stricter the standard, the lower the cutoff level and the larger the gap between the expenditure categories: Even households with a small amount of capital will refrain from replacing it if the standard pushes them too far from their individually optimal investment.

Secondly, we characterize the *aggregate* effects of a weak standard. In general, such a standard increases the aggregate investment in energy-efficiency capital and its price, and reduces the aggregate energy consumption and its price. However, if the capital supply is inelastic, then a weak standard will only increase the capital price without affecting the energy market.

Thirdly, we demonstrate the aggregate effects of a further tightening of the standard. The stricter the standard, the less effective it is at improving overall energy efficiency and reducing aggregate energy consumption. At some critical value of the standard, energy demand is minimized. Further tightening the standard still stimulates aggregate investment, but it is concentrated on a few households, while so many other households are discouraged from investing that aggregate energy consumption increases. Ultimately, a sufficiently strict standard will result in higher aggregate energy consumption than no standard at all.

Fourthly, we derive and decompose the *rebound effect* – that is, the percentage overestimation of energy savings – of a stricter standard. This rebound effect consists of the *direct rebound effect*, the *price effect* and the *investment effect*. The first, which is well known in the literature, results from the increased demand for energy services by investing households, while the second results from the changed prices of capital and energy. The investment effect is a standard-specific rebound channel that results from the fact that a stricter standard discourages households from investing. In our central calibration of the corporate average fuel economy (CAFE) standard, taking the investment decision into account increases the rebound effect from 40 percent to 99 percent, making any further tightening of the standard virtually ineffective.

Fifthly, we discuss welfare and distributional issues. The costs and benefits of a minimum-efficiency standard for a household depend on the household's initial energy efficiency. A household with high energy efficiency would not invest anyway and therefore benefits from a minimum-efficiency standard if its introduction reduces the energy price. By contrast, a household with low energy efficiency that plans to invest bears the costs of a policy that, firstly, mandates higher energy efficiency than the household would voluntarily choose and, secondly, increases the aggregate demand for energy-efficiency capital, thereby raising its price. A key insight here is that, from the perspective of utilitarian welfare maximization, the gap between capital and energy expenditures created by the standard can be understood as the deadweight loss of the policy.

Finally, since a minimum efficiency standard can neither cost-effectively reduce energy

consumption nor cost-effectively increase capital investment, we compare its distributional effects with those of an energy tax and a capital subsidy. On the one hand, reducing energy consumption by one percent through an energy tax leads to a smaller rise in the capital price than through a standard, and *increases* the energy price. Consequently, capital firms and non-investing households (tend to) prefer the standard, while energy firms and investing households (tend to) prefer the tax. On the other hand, raising capital investment by one percent through a capital subsidy leads to a larger reduction in the energy price than through a standard, and *decreases* the capital price. Thus, capital firms and energy firms prefer the standard, while investing households and non-investing households (tend to) prefer the subsidy. The existence of a minimum-efficiency standard could therefore indicate a strong political influence of capital firms, or a weak political influence of investing households.

This article combines two strands of literature: the adverse effects of vintage-differentiated regulation on the scrapping of old capital (“Gruenspecht effect”), and the adverse effects of higher energy efficiency on energy consumption (“rebound effect”). Regarding the former effect, Gruenspecht (1982) emphasizes that stricter exhaust or safety standards for new cars extend the lifespan of old cars, thereby increasing aggregate emissions or reducing overall safety in the short run. Stavins (2006) provides a comprehensive overview of vintage-differentiated regulation and identifies two sectors where the Gruenspecht effect is particularly relevant: the US automotive industry with its exhaust, safety and efficiency standards, and the US power sector with the New Source Review program. Heutel (2011) finds that the New Source Review program reduces the modernization or scrapping of old power plants, but increases the modernization of existing power plants that are already affected by the regulation. Regarding the US automotive industry, Jacobsen and van Benthem (2015) analyze the effects of stricter CAFE standards. They estimate the elasticity of the scrap rate with respect to used vehicle prices to be -0.7 (similarly, Bento et al. (2018) estimate a scrap elasticity of -0.4). Also analyzing the effects of stricter standards on vehicle prices, Jacobsen and van Benthem (2015) then derive a “used car leakage” (Gruenspecht effect) of 13 to 16 percent. Finally, Jacobsen et al. (2023) analyze how stricter exhaust standards reduce the scrap rate via new vehicle prices. All these contributions have an empirical focus. By contrast, we develop an analytically solvable theoretical model in which the scrap elasticity is not a point estimate but depends on the stringency of the minimum-efficiency standard.

The literature on the Gruenspecht effect focuses on the scrapping decision and abstracts from other effects of regulation on energy consumption. For example, the above models assume exogenous energy prices and exogenous energy consumption of a given vehicle or power plant. On the other hand, the literature on the rebound effect analyzes how improvements in energy efficiency affect energy consumption. Improvements in energy efficiency increase the demand for energy services, which reduces potential energy savings and may even increase energy consumption. This adverse effect is known as *Jevons paradox* (Jevons, 1865), *Khazzoom–Brookes postulate* (Khazzoom, 1980; Brookes, 1990), *backfire* (Saunders, 1992, 2000) or *conservation paradox* (Wirl, 1997). Gillingham et al. (2016), Saunders et al. (2021) and Rajabi (2022) provide overviews on theoretical contributions and empirical estimates, and de-

compose the rebound effect into four channels: The *direct rebound effect* described above, the *indirect rebound effect* from shifted demands for all other goods, the *price effect* from altered equilibria on the goods markets, and the *growth effect* from dynamic changes in energy consumption. Our framework allows the simultaneous analysis of the direct rebound effect and the price effect together with the Gruenspecht effect. Other theoretical contributions to the rebound effect include static models without (Ghosh and Blackhurst, 2014; Borenstein, 2015; Chan and Gillingham, 2015) and with (Fullerton and Ta, 2020; Lemoine, 2020; Blackburn and Moreno-Cruz, 2021; Böhringer and Rivers, 2021; da Rocha and de Almeida, 2021) price effects as well as dynamic models (Hart, 2018; Rausch and Schwerin, 2018; Casey, 2024). Most of these papers analyze exogenous and costless improvements in energy efficiency,³ and none of them take investment decisions at the extensive margin into account. We combine the literature on the Gruenspecht effect and on the rebound effect by considering both the adverse effects of stricter standards on the scrapping of old capital and the adverse effects of higher energy efficiency on energy consumption.

Common justifications for the introduction of standards are (environmental) externalities from energy consumption or internalities from energy efficiency investments (e.g. undervalued savings potential) leading to an *energy efficiency gap* (Jaffe and Stavins, 1994; Gillingham et al., 2009; Allcott and Greenstone, 2012; Gillingham and Palmer, 2014; Allcott, 2016; Gerarden et al., 2017). For example, the National Highway Traffic Safety Administration states that CAFE standards can increase welfare only if there are non-internalized externalities or non-internalized internalities (NHTSA, 2024, Section 2.1.4). Whether and to what extent there are internalities from energy efficiency investments is controversially discussed in the literature. With regard to the automobile market, some papers find little evidence of consumer misperceptions (Busse et al., 2013; Sallee et al., 2016; Grigolon et al., 2018), while others find strong evidence (Allcott and Wozny, 2014; Gillingham et al., 2021). In any case, energy taxes or capital subsidies, rather than standards, are typically the policy instruments that can efficiently internalize externalities from energy consumption or internalities from energy efficiency investments (Chan and Globus-Harris, 2023). We show that the different distributional effects of these instruments can explain the introduction of a standard through the political influence of interest groups or fairness considerations.

The results of the literature on such distributional effects are mixed. With regard to the CAFE standard, some papers find it to be regressive (Jacobsen, 2013; Davis and Knittel, 2019) or more regressive than a carbon tax (Davis and Knittel, 2019; Levinson, 2019; Metcalf, 2019), while others find it to be progressive (Leard et al., 2023) or more progressive than a carbon tax (Zhao and Mattauch, 2022).⁴ We complement this literature by explicitly taking investment

³The exceptions are Borenstein (2015), who analyzes exogenous but costly improvements in energy efficiency, Fullerton and Ta (2020), who analyze endogenous investments in energy efficiency or exogenous but costly improvements in energy efficiency through energy efficiency standards, Rausch and Schwerin (2018), who analyze endogenous investments in energy efficiency, and Casey (2024), who analyzes exogenous but costly improvements in energy efficiency through energy efficiency R&D subsidies.

⁴Durrmeyer and Samano (2018) find that manufacturers of high- and low-fuel-consuming vehicles and consumers prefer taxes and subsidies to standards, while manufacturers of medium-fuel-consuming vehicles prefer standards.

decisions into account and thus distinguishing between investing consumers with low energy efficiency and non-investing consumers with high energy efficiency as well as between capital producers and energy producers.

The paper proceeds as follows. Section 2 analyzes a household's demand for energy and for energy-efficiency capital, first without and then with a minimum-efficiency standard. Section 3 first describes aggregate supply and demand for energy and capital, and then analyzes the equilibrium effects of minimum-efficiency standards, first for a weak standard and then for a strong standard. Functional forms are introduced when necessary. Section 4 analyzes adverse effects of energy-efficiency policy. First, we decompose the rebound effect and show that the uncovered investment effect can account for a large part of the total rebound effect. Second, we analyze the negative welfare effects and the distributional consequences of a minimum-efficiency standard, compare them to those of an energy tax and a capital subsidy, and discuss political economic implications. Finally, Section 5 concludes.

2 Individual Demand

2.1 The Setting

Suppose that households have preferences over consumption of a numeraire good, X , and consumption of energy services, S . Household i 's utility is

$$u_i = X_i + B(S_i), \quad (2.1)$$

where the energy-services benefit function $B_i \equiv B(S_i)$ is increasing in S_i and strictly concave, with $\lim_{S \rightarrow 0} B'(S) = \infty$ and $\lim_{S \rightarrow \infty} B'(S) = 0$. Energy services are obtained by combining energy E , which can represent fuel or electricity, and capital K , so that household i 's consumption of energy services is $S_i \equiv K_i E_i$.⁵ For cars, K_i are miles per gallon and S_i are miles driven. In general, K_i may represent the "energy-efficiency capital" – or "efficiency capital" for short – embodied in a car, a space-heating system, the building insulation, or household appliances such as refrigerators or washing machines. In the investment decision considered below, we assume that such household capital goods are continuously scalable at the time of purchase, and that their only characteristic is the amount of energy services per unit of energy that they provide. For instance, if the household has a better space-heating system that provides a warmer home with the same amount of energy, K_i is greater.⁶ Stating that a household has a more energy-efficient appliance (or car, space-heating system, etc.) is thus equivalent to stating that it has more capital.

The household's budget is $X_i + pE_i + I_i = Y_i$, where p is the energy price, I are investment

⁵For the proofs of our results, we use the general benefit function $B(K_i, E_i)$ in the Appendix.

⁶The simplifying assumption in the present model is that the household is free to choose this characteristic at the time of purchase, which is a shortcut for producers to offer the varieties that consumers demand.

expenditures and Y_i is exogenous income. Thus, utility becomes

$$u_i = Y_i - pE_i - I_i + B(S_i). \quad (2.2)$$

In the following, we analyze the household's optimal behavior in two stages. First, we derive the energy demand given the level of capital. Then, the household's capital level is endogenized.

2.2 Energy Demand

If the household has no capital ($K_i = 0 \implies S_i = 0$), energy consumption has only costs and no benefits, so the household will choose $E_i = 0$. For $K_i > 0$, $\lim_{S \rightarrow 0} B'(S) = \infty$ and $\lim_{S \rightarrow \infty} B'(S) = 0$ imply that there is a strictly positive amount of E_i fulfilling the first-order condition

$$B'(S_i)K_i = p. \quad (2.3)$$

This implicitly defines the household's energy demand and thus its demand for energy services as functions of K_i and p , i.e. $K_i E^*(K_i, p) \equiv S^*(K_i, p) \equiv S_i^*$. Differentiating (2.3) and rearranging yields the elasticities of energy demand with respect to the energy price, $\varepsilon_{E,p}$, and with respect to the household's amount of capital, $\varepsilon_{E,K}$:

$$\varepsilon_{E,p}(K_i, p) \equiv \frac{\partial E^*(K_i, p)/E^*(K_i, p)}{\partial p/p} = -\frac{1}{\beta(S_i^*)} = \varepsilon_{S,p}(K_i, p), \quad (2.4a)$$

$$\varepsilon_{E,K}(K_i, p) \equiv \frac{\partial E^*(K_i, p)/E^*(K_i, p)}{\partial K_i/K_i} = \frac{1}{\beta(S_i^*)} - 1 = \varepsilon_{S,K}(K_i, p) - 1, \quad (2.4b)$$

where $\beta(S_i) \equiv -B''(S_i)S_i/B'(S_i) > 0$ denotes the absolute value of the elasticity of marginal energy benefits with respect to energy services. From (2.4), we infer

$$\varepsilon_{S,K}(K_i, p) = 1 + \varepsilon_{E,K}(K_i, p) = -\varepsilon_{E,p}(K_i, p) = -\varepsilon_{S,p}(K_i, p) = \frac{1}{\beta(S_i^*)}, \quad (2.5)$$

where $\varepsilon_{S,K}(K_i, p)$ represents the “direct rebound effect” (Greening et al., 2000).⁷ It measures the relative increase in the demand for energy services induced by an exogenous increase in energy efficiency. Theoretically, the direct rebound effect can exceed one, in which case an increase in energy efficiency increases energy demand and thus “backfires” (see e.g. Voss, 2015). However, the direct rebound effect tends to be small for household energy services – Sorrell et al. (2009) and Gillingham et al. (2016) find direct rebound effects for personal transport, space heating and space cooling in the range of 0–60%. We therefore assume capital

⁷Saunders (2000) establishes $\varepsilon_{S,K}(K_i, p) = 1 + \varepsilon_{E,K}(K_i, p)$, while Sorrell and Dimitropoulos (2008) discuss $\varepsilon_{S,K}(K_i, p) = 1 + \varepsilon_{E,K}(K_i, p) = -\varepsilon_{E,p}(K_i, p) = -\varepsilon_{S,p}(K_i, p)$.

and energy to be substitutes, i.e.

$$\frac{\partial^2 B_i}{\partial K \partial E} = B'(S_i)[1 - \beta(S_i)] < 0, \quad (2.6)$$

which implies $\beta(S_i) > 1$ and, thus, $\varepsilon_{S,K}(K_i, p) \in (0, 1)$. This exclusion of backfire from the direct rebound effect allows that energy-efficiency policy could, at least in principle, make sense as a policy to reduce energy consumption, so that the present paper can focus on other aspects of such a policy.

Finally, substituting $E^*(K_i, p)$ into (2.2), the household's optimized utility is

$$u_i = U_i(K_i, p, I_i) = Y_i - pE^*(K_i, p) - I_i + B(S_i^*). \quad (2.7)$$

2.3 Unconstrained Investment

Suppose that the household is endowed with an amount of capital $K_{i,0}$. Keeping and using it, the household's utility is given by (2.7) for $I_i = 0$ and $K_i = K_{i,0}$, i.e. $U_i(K_{i,0}, p, 0)$. Taking (2.3) into account, energy-efficiency capital increases utility, i.e. $\partial U_i(K_{i,0}, p, 0) / \partial K = B'(S^*(K_{i,0}, p))E^*(K_{i,0}, p) > 0$, such that $U_i(K_{i,0}, p, 0)$ is greater with a larger endowment. Now instead of using $K_{i,0}$, the household could scrap it and buy a new capital good with an amount of energy-efficiency capital that maximizes $U_i(K_i, p, I_i)$. Thereby, the investment corresponds to the expenditure on the capital good, i.e. $I_i = hK_i$ with h as the capital price, so that utility from (2.7) becomes $U_i(K_i, p, hK_i)$. The household's optimal amount of capital K° is defined by

$$B'(S^*(K^\circ, p))E^*(K^\circ, p) = h, \quad (2.8)$$

where we use K° instead of K_i° because it does not depend on the household's characteristics. As shown in Appendix A.1, $U_i(K_i, p, hK_i)$ is strictly concave in K_i , $K^\circ = K^\circ(h, p)$ is strictly positive, and it is decreasing in the capital price and increasing in the energy price. We suppress this functional dependence in the following in order to keep the notation clear, and proceed in the same way in similar cases below. Using $B'(S_i) = p/K_i$ from (2.3) in (2.8) yields:

$$hK^\circ = pE^*(K^\circ, p). \quad (2.9)$$

That is, the household balances its expenditures on capital and energy, because they are equally effective in providing energy services. The optimization yields $U_i(K^\circ, p, hK^\circ)$. Comparing the two alternatives, replacing the endowment is better if

$$B(S^*(K^\circ, p)) - B(S^*(K_{i,0}, p)) + p[E^*(K_{i,0}, p) - E^*(K^\circ, p)] \geq hK^\circ. \quad (2.10)$$

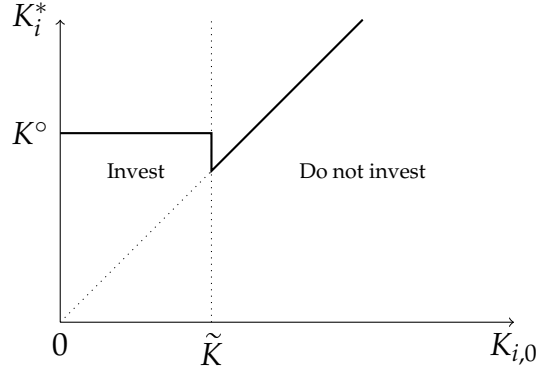


Figure 1: Household Capital with Optimal Investment

The left-hand side shows the advantages of having $K^\circ > K_{i,0}$, namely an increase in energy services and a reduction in energy expenditures; see (2.5). However, this requires the expenditures shown on the right-hand side. There is an endowment $K_{i,0} = \tilde{K} > 0$ that makes the household just indifferent:⁸

$$B(S^*(K^\circ, p)) - B(S^*(\tilde{K}, p)) + p [E^*(\tilde{K}, p) - E^*(K^\circ, p)] = hK^\circ. \quad (2.11)$$

This equation implicitly defines the cutoff level as a function of the prices of energy and capital: $\tilde{K} = \tilde{K}(h, p)$. The optimal amount of capital K_i^* and the investment expenditures of household i are

$$(K_i^*(h, p), I_i^*(h, p)) = \begin{cases} (K^\circ(h, p), hK^\circ(h, p)) & \text{if } K_{i,0} \in [0, \tilde{K}), \\ (K_{i,0}, 0) & \text{if } K_{i,0} \in [\tilde{K}, \infty). \end{cases} \quad (2.12)$$

K_i^* is discontinuous in the endowment. A household with less than \tilde{K} will invest and afterwards have K° . A household with slightly more than \tilde{K} will not accept the cost of new capital and will therefore have less than K° . A household with much more than \tilde{K} , i.e. $K_{i,0} > K^\circ$, will also keep it. Figure 1 illustrates the investment decision.

2.4 Investment with a Minimum-Efficiency Standard

We now consider a minimum-efficiency standard policy. This policy prescribes that *if* a household invests, it has to choose $K_i \geq \underline{K}$. Since unconstrained investment implies $K_i = K^\circ$, a standard is binding if $\underline{K} > K^\circ$. Then, $K_i = \underline{K}$ will hold for every investing household. In the following, when comparing two levels of the minimum-efficiency standard $\underline{K}' > \underline{K}$, the former standard will be called *stricter* than the latter.

Which effects will the introduction of a minimum-efficiency standard have? Firstly, there is an effect at the intensive margin: If the household still invests, its investment has to be higher. This pushes the household away from privately optimal cost minimization; while its energy consumption is still optimal for a given amount of capital ((2.3) still holds), the

⁸Note that $K^\circ > 0$ implies $B(S^*(K^\circ, p)) - pE^*(K^\circ, p) - hK^\circ > B(0) - pE^*(0, p)$. Thus, $\tilde{K} > 0$.

optimal-capital condition (2.8) no longer holds. Instead,

$$\frac{\partial U_i(\underline{K}, p, h\underline{K})}{\partial \underline{K}} = B'(S^*(\underline{K}, p))E^*(\underline{K}, p) - h < 0 \quad (2.13)$$

if $\underline{K} > K^\circ$, which also implies that instead of the expenditure balance (2.9), we have

$$h\underline{K} > pE^*(\underline{K}, p) \quad (2.14)$$

if $\underline{K} > K^\circ$. The minimum-efficiency standard forces the household to have too much capital to minimize cost, and the investment expenditures exceed its expenditures for energy. Moreover, the stricter the standard, the larger the deviation between the expenditures:

$$\frac{d[h\underline{K} - pE^*(\underline{K}, p)]}{d\underline{K}} = h - \varepsilon_{E,K}(\underline{K}, p) \frac{pE^*(\underline{K}, p)}{\underline{K}} \in (h, 2h), \quad (2.15)$$

where we have used $\varepsilon_{E,K}(\underline{K}, p) \in (-1, 0)$ from (2.5) and $pE^*(\underline{K}, p)/\underline{K} < h$ from (2.14).

Secondly, because the household is kept from its private optimum, the minimum-efficiency standard reduces after-investment utility, and this has an effect at the extensive margin – that is, the decision whether to invest is affected. In (2.10), \underline{K} takes the place of K° . With the minimum-efficiency standard, the household will scrap the old capital and buy an amount \underline{K} if

$$U_i(\underline{K}, p, h\underline{K}) \geq U_i(K_{i,0}, p, 0). \quad (2.16)$$

The amount of capital for which this is fulfilled with equality is the new cutoff level \check{K} :

$$B(S^*(\underline{K}, p)) - B(S^*(\check{K}, p)) + p[E^*(\check{K}, p) - E^*(\underline{K}, p)] = h\underline{K}. \quad (2.17)$$

The cutoff level depends on prices and the standard: $\check{K} = \check{K}(h, p, \underline{K})$. The optimal amount of capital K_i^* and the investment expenditures of household i are

$$(K_i^*(h, p, \underline{K}), I_i^*(h, p, \underline{K})) = \begin{cases} (\underline{K}, h\underline{K}) & \text{if } K_{i,0} \in [0, \check{K}), \\ (K_{i,0}, 0) & \text{if } K_{i,0} \in [\check{K}, \infty). \end{cases} \quad (2.18)$$

A standard above K° will imply that the household is more reluctant to invest such that $\check{K} < \tilde{K}$, but it has to choose $\underline{K} > K^\circ$ if it invests. Figure 2 illustrates these effects.

To see how the cutoff level \check{K} depends on prices and the standard, we differentiate (2.17) and rearrange:

$$\varepsilon_{\check{K},h}(h, p, \underline{K}) \equiv \frac{\partial \check{K}/\check{K}}{\partial h/h} = -\frac{h\underline{K}}{p\check{E}} = -\frac{h}{\frac{\partial \check{B}}{\partial \check{K}}} \frac{\underline{K}}{\check{K}} \in \left(-\frac{\underline{K}}{\check{K}}, -0.5\right), \quad (2.19a)$$

$$\varepsilon_{\check{K},p}(h, p, \underline{K}) \equiv \frac{\partial \check{K}/\check{K}}{\partial p/p} = \frac{\check{E} - \underline{E}}{\check{E}} = \frac{h}{\frac{\partial \check{B}}{\partial \check{K}}} \frac{\underline{K}}{\check{K}} - \frac{B - \check{B}}{\frac{\partial \check{B}}{\partial \check{K}}} \in \left(0, |\varepsilon_{\check{K},h}(h, p, \underline{K})|\right), \quad (2.19b)$$

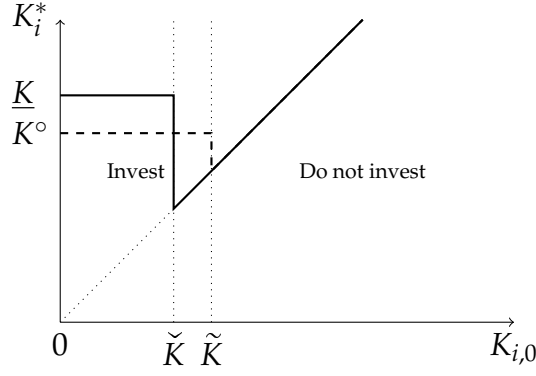


Figure 2: Household Capital with Optimal Investment, given the Minimum-Efficiency Standard

$$\varepsilon_{\check{K}, \underline{K}}(h, p, \underline{K}) \equiv \frac{\partial \check{K} / \check{K}}{\partial \underline{K} / \underline{K}} = -\frac{h\underline{K} - p\underline{E}}{p\check{E}} = -\frac{h - \frac{\partial \check{B}}{\partial \check{K}} \frac{\underline{K}}{\check{K}}}{\frac{\partial \check{B}}{\partial \check{K}}} \in \left(\varepsilon_{\check{K}, h}(h, p, \underline{K}), 0 \right], \quad (2.19c)$$

where $\check{E} \equiv E^*(\check{K}, p)$, $\underline{E} \equiv E^*(\underline{K}, p)$, $\check{B} \equiv B(\check{K}, \check{E})$, $\underline{B} \equiv B(\underline{K}, \underline{E})$ and $\partial \check{B} / \partial \check{K} > h \geq \partial \underline{B} / \partial \underline{K}$. The influence of the capital price on the cutoff level is clearly negative: With a higher price of capital, the household would be more willing to stick to its old space-heating system instead of replacing it. Conversely, with a higher price of energy, the household is more willing to scrap its capital endowment, because energy usage with the new amount of capital would be lower. Note that the cutoff level is more sensitive to capital price changes than to energy price changes: A higher price of capital increases the costs of the investment, namely $h\underline{K}$, whereas a higher price of energy increases only part of the benefits of the investment, namely $p(\check{E} - \underline{E})$ but not $\underline{B} - \check{B}$. Finally, the stricter the standard, the more the potential investment deviates from the optimal investment, such that the cutoff level decreases and less households invest.

We now analyze how strongly \check{K} and the elasticities react to an increase in \underline{K} . For this analysis, the following wording is useful:

Definition 1 (Minimum-Efficiency Standard Classifications). A minimum-efficiency standard that sets \underline{K} marginally above $\underline{K} = K^0$ is called a *weak (minimum-efficiency) standard*. Precisely, we refer to the effects of a weak standard when evaluating the marginal effects of a minimum-efficiency standard for a value of $\underline{K} = K^0$. ($\underline{K} = K^0$ also implies $\check{K} = \tilde{K}$ by the definitions of \check{K} in (2.11), and of \tilde{K} in (2.17).) Any minimum-efficiency standard above this level is called a *strong (minimum-efficiency) standard*.

The following lemma proved in Appendix A.2 summarizes the household-level analysis:

Lemma 1 (Individual Effect of \underline{K} on \check{K}). For $\underline{K} = K^0$, we have $\frac{\partial \check{K}}{\partial \underline{K}} = 0$ and $\frac{\partial |\varepsilon_{\check{K}, \underline{K}}|}{\partial \underline{K}}, \frac{\partial |\varepsilon_{\check{K}, h}|}{\partial \underline{K}}, \frac{\partial \varepsilon_{\check{K}, p}}{\partial \underline{K}} > 0$. For $\underline{K} > K^0$, we have $\frac{\partial \check{K}}{\partial \underline{K}} \in (-1, 0)$. Finally, $\lim_{\underline{K} \rightarrow \infty} \check{K} = 0$.

Thus, tightening a weak standard makes the cutoff level \check{K} more sensitive to changes in the standard and prices. Furthermore, (i) a weak minimum-efficiency standard hardly affects the cutoff level \check{K} and will thus reduce an investing household's energy consumption, even

if the household was almost indifferent about investing, (ii) making it stricter monotonically decreases the capital endowment below which the household would decide to invest, such that a strong standard reduces an investing household's energy consumption if the household still invests, but increases its energy consumption if the standard deters the household from investing, and (iii) with a sufficiently strict standard the household will not invest, implying that a sufficiently strict standard increases energy consumption of all households that would invest if there were no standard.

3 Aggregate Analysis

3.1 Aggregate Investment and Aggregate Energy Consumption with a Minimum-Efficiency Standard

We turn to the equilibrium analysis of aggregate energy consumption and aggregate (efficiency-capital) investment. There is a unit-size continuum of households. Suppose that the capital endowment follows a cumulative distribution function $G(K_{i,0})$ with a density $g(K_{i,0}) \equiv G'(K_{i,0})$. With a minimum-efficiency standard, the share of households that invest is $G(\check{K})$. Thus, after investment, the share $G(\check{K})$ of households will have capital \underline{K} , and the share $1 - G(\check{K})$ has capital distributed between \check{K} and ∞ (or some maximum amount of capital); this span includes \underline{K} . Aggregate investment demand and aggregate energy demand thus are

$$I(h, p, \underline{K}) = \int_0^{\check{K}(h, p, \underline{K})} g(K_{i,0}) \underline{K} dK_{i,0} = G(\check{K}(h, p, \underline{K})) \underline{K}, \quad (3.1a)$$

$$\begin{aligned} E(h, p, \underline{K}) &= \int_0^{\check{K}(h, p, \underline{K})} g(K_{i,0}) E^*(\underline{K}, p) dK_{i,0} + \int_{\check{K}(h, p, \underline{K})}^{\infty} g(K_{i,0}) E^*(K_{i,0}, p) dK_{i,0} \\ &= G(\check{K}(h, p, \underline{K})) E^*(\underline{K}, p) + \int_{\check{K}(h, p, \underline{K})}^{\infty} g(K_{i,0}) E^*(K_{i,0}, p) dK_{i,0}. \end{aligned} \quad (3.1b)$$

Suppose that there are price-taking firms supplying capital and energy. Define the profits of the sectors' representative firms by

$$\pi_k = \Pi_k(k) = hk - C_k(k), \quad (3.2a)$$

$$\pi_e = \Pi_e(e) = pe - C_e(e), \quad (3.2b)$$

where k and e are the supplied quantities, and C_k and C_e are (convex) cost functions. From the first-order conditions, we obtain the supply functions $k(h)$ and $e(p)$ (with $k'(h) = 1/C_k''(k)$ and $e'(p) = 1/C_e''(e)$). In equilibrium,

$$k(h^\bullet) = G(\check{K}^\bullet) \underline{K}, \quad (3.3a)$$

$$e(p^\bullet) = G(\check{K}^\bullet) E^*(\underline{K}, p^\bullet) + \int_{\check{K}^\bullet}^{\infty} g(K_{i,0}) E^*(K_{i,0}, p^\bullet) dK_{i,0}, \quad (3.3b)$$

where $\check{K}^\bullet \equiv \check{K}(h^\bullet, p^\bullet, \underline{K})$. The \bullet denotes the equilibrium values, but we drop this in the following in order to keep the notation clear.

We now consider how a minimum-efficiency standard affects the equilibrium. We have already seen that a stricter standard implies that a household would need a lower capital endowment to choose investing over keeping the old capital. From the aggregate perspective, we can say that less households invest. However, we also know that any household that invests now has to choose a higher amount. If (and only if) this intensive-margin effect outweighs the extensive-margin effect, aggregate investment is increased by the standard. Moreover, energy demand is reduced if (and only if) the increase of investment at the intensive margin also reduces energy consumption to a larger extent than the reduction of investment at the extensive margin increases it.

Define the elasticities

$$\eta(h) \equiv \frac{\partial k(h)/k(h)}{\partial h/h}, \quad \theta(p) \equiv \frac{\partial e(p)/e(p)}{\partial p/p}, \quad \gamma(K) \equiv \frac{\partial G(K)/G(K)}{\partial K/K}, \quad (3.4)$$

where η is the elasticity of efficiency-capital supply with respect to the price, θ is the elasticity of energy supply with respect to the price, and γ is the elasticity of the *share* of households with capital below K with respect to that amount.

To determine the effects of the standard on the equilibrium prices, we differentiate (3.3) and solve for the relative price changes $\hat{h} \equiv dh/h$ and $\hat{p} \equiv dp/p$ dependent on the relative change in the standard $\hat{K} \equiv dK/K$ in Appendix A.3. Defining the equilibrium elasticities $\Omega_{p,K}(\underline{K}) \equiv \hat{p}^\bullet(\underline{K})/\hat{K}$ and $\Omega_{h,K}(\underline{K}) \equiv \hat{h}^\bullet(\underline{K})/\hat{K}$ for the prices, and $\Omega_{k,K}(\underline{K}) \equiv \hat{k}^\bullet(\underline{K})/\hat{K}$ and $\Omega_{e,K}(\underline{K}) \equiv \hat{e}^\bullet(\underline{K})/\hat{K}$ for the quantities, we obtain:

$$\Omega_{h,K}(\underline{K}) = \frac{\chi(\underline{K}) [\theta - \varepsilon_{E,p}] \left[1 + \check{\gamma} \varepsilon_{\check{K},K} \right] + \check{\gamma} \varepsilon_{\check{K},p} \left[\varepsilon_{E,K} + \frac{\check{E}-E}{E} \right]}{\chi(\underline{K}) [\theta - \varepsilon_{E,p}] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-E}{E}} \leq \frac{1}{\eta}, \quad (3.5a)$$

$$\Omega_{p,K}(\underline{K}) = \frac{\eta \left[\varepsilon_{E,K} - \check{\gamma} \varepsilon_{\check{K},K} \frac{\check{E}-E}{E} \right] - \check{\gamma} \varepsilon_{\check{K},h} \left[\varepsilon_{E,K} + \frac{\check{E}-E}{E} \right]}{\chi(\underline{K}) [\theta - \varepsilon_{E,p}] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-E}{E}} \geq \frac{\varepsilon_{E,K}}{\chi(\underline{K}) [\theta - \varepsilon_{E,p}]}, \quad (3.5b)$$

$$\Omega_{k,K}(\underline{K}) = \eta \Omega_{h,K}(\underline{K}) \leq 1, \quad (3.5c)$$

$$\Omega_{e,K}(\underline{K}) = \theta \Omega_{p,K}(\underline{K}) \geq \frac{\theta \varepsilon_{E,K}}{\chi(\underline{K}) [\theta - \varepsilon_{E,p}]} > \varepsilon_{E,K}, \quad (3.5d)$$

where $\check{\gamma} \equiv \gamma(\check{K})$, $\varepsilon_{E,p} \equiv \varepsilon_{E,p}(\underline{K})$ and $\varepsilon_{E,K} \equiv \varepsilon_{E,K}(\underline{K})$, and where

$$\chi(\underline{K}) = 1 + \int_{\check{K}}^{\infty} \frac{g(K_{i,0})}{G(\check{K})} \frac{\theta - \varepsilon_{E,p}(K_{i,0})}{\theta - \varepsilon_{E,p}} \frac{E_{i,0}}{E} dK_{i,0} > 1. \quad (3.6)$$

In equilibrium, the prices p and h are functions of the standard \underline{K} , such that the equilibrium elasticities and χ are just functions of the standard \underline{K} . (3.5) reveals that a one-percent increase in the standard increases aggregate investment by less than one percent (or reduces it). Fur-

thermore, such an increase reduces aggregate energy consumption by less than it directly reduces the energy consumption of the investing households (or increases it).

In general, we cannot say whether a tightening of the standard increases aggregate investment and/or reduces aggregate energy consumption, because the changed prices and the reduced marginal benefit of investment will affect how many households invest. Only in two special cases are the effects immediately clear. First, if no household is indifferent about investing, $g(\check{K}) = 0 \implies \check{\gamma} = 0$. Then, a one-percent increase in the standard increases aggregate investment by one percent, $\Omega_{k,\underline{K}}(\underline{K}) = 1$, and reduces aggregate energy consumption, $\Omega_{e,\underline{K}}(\underline{K}) = \theta \varepsilon_{E,K} / \{\chi(\underline{K})[\theta - \varepsilon_{E,p}]\} \leq 0$, because it reduces the energy consumption of the investing households through higher capital endowment (direct effect) more than it increases the energy consumption of the non-investing households through lower energy prices (indirect effect). Second, if the standard is so strict that no household invests, $G(\check{K}) = 0 \implies \check{\gamma} \rightarrow \infty$. Then, further increases in the standard will have no effect. Otherwise, the effect of a stricter standard on the cutoff level \check{K} shown in the following Lemma (proved in Appendix A.4) becomes relevant:

Lemma 2 (Aggregate Effect of \underline{K} on \check{K}). *Suppose $\check{\gamma} \in (0, \infty)$. For $\underline{K} = K^\circ$, $\eta \rightarrow \infty$, $\theta \rightarrow \infty$, we have $\frac{d\check{K}}{d\underline{K}} = 0$; otherwise, $\frac{d\check{K}}{d\underline{K}} < 0$. We always have $\frac{dE}{d\underline{K}} < 0$ and $\frac{d[G(\check{K})E/e]}{d\underline{K}} < 0$.*

Thus, although the capital price can decrease and the energy price can increase, a stricter standard in general implies that fewer households invest. In contrast to the results for an individual household (Lemma 1), this is already true for a weak standard. In case of a weak standard, either the capital price increases or the energy price decreases or both, which depresses investment. Furthermore, the investing households consume less energy, even if the energy price falls. Finally, the share of energy consumed by the investing households is decreasing in the standard.

3.2 The Effects of a Weak Minimum-Efficiency Standard

We now analyze the reaction of the energy market and the efficiency-capital market on a weak minimum-efficiency standard. If the capital price or the energy price are constant, most effects of a weak standard are immediately clear without additional assumptions. In particular, inspection of (3.5) reveals:⁹

Proposition 1 (The Effects of a Weak Minimum-Efficiency Standard). *Suppose $\underline{K} = K^\circ$ and $\check{\gamma} \in (0, \infty)$. Then:*

- 1.) *For $\eta \rightarrow \infty$ and $\theta \rightarrow \infty$, we have $\Omega_{h,\underline{K}} = \Omega_{p,\underline{K}} = 0$, $\Omega_{k,\underline{K}} = 1$ and $\Omega_{e,\underline{K}} \in (\varepsilon_{E,K}, 0)$.*
- 2.) *For $\eta \rightarrow \infty$ and $\theta \in [0, \infty)$, we have $\Omega_{h,\underline{K}} = 0$, $\Omega_{p,\underline{K}} < 0$ and $\Omega_{e,\underline{K}} \in (\varepsilon_{E,K}, 0]$, where $\Omega_{e,\underline{K}} = 0 \iff \theta = 0$.*
- 3.) *For $\eta \in [0, \infty)$ and $\theta \rightarrow \infty$, we have $\Omega_{h,\underline{K}} > 0$, $\Omega_{p,\underline{K}} = 0$ and $\Omega_{k,\underline{K}} \in [0, 1)$, where $\Omega_{k,\underline{K}} = 0 \iff \eta = 0$.*

⁹For $\underline{K} \geq K^\circ$ and $\check{\gamma} = 0$, we have $\Omega_{h,\underline{K}} = 1/\eta \geq 0$, $\Omega_{p,\underline{K}} = \varepsilon_{E,K} / \{\chi(\underline{K})[\theta - \varepsilon_{E,p}]\} \leq 0$, $\Omega_{k,\underline{K}} = 1$ and $\Omega_{e,\underline{K}} = \theta \varepsilon_{E,K} / \{\chi(\underline{K})[\theta - \varepsilon_{E,p}]\} \leq 0$.

If both supply functions are perfectly elastic, both prices are constant. Then, a weak standard does not affect the share of investing households, since $\varepsilon_{\check{K},\underline{K}} = 0$, but these households have to invest more and reduce their energy consumption ($\varepsilon_{\underline{E},\underline{K}} < 0$). On the other hand, the non-investing households have no incentive to change energy consumption, which explains $\Omega_{e,\underline{K}} \in (\varepsilon_{\underline{E},\underline{K}}, 0)$. If only the capital supply function is perfectly elastic, a weak standard depresses energy demand and hence the energy price. However, it is not clear whether aggregate investment increases as fewer households invest ($\varepsilon_{\check{K},p} > 0$). Finally, if only the energy supply function is perfectly elastic, a weak standard increases capital demand and hence the capital price. The investing households reduce their energy consumption, but since a household that is deterred from investing uses more energy and fewer households invest ($\varepsilon_{\check{K},h} < 0$), it depends on the demand and supply functions whether aggregate energy consumption decreases.

To further analyze how a minimum-efficiency standard affects the energy market and the efficiency-capital market, we make the following assumption throughout:¹⁰

Assumption 1 (Benefit Function). The benefit function is isoelastic:

$$B(S_i) \equiv b \frac{S_i^{1-\beta} - 1}{1-\beta}, \quad (3.7)$$

where $b > 0$ and $\beta > 1$ by (2.5).

In Appendix A.5, we derive the corresponding explicit versions of the results from Section 2. In particular, the isoelastic benefit function implies that the elasticities of energy demand from (2.4) are constant and given by $\varepsilon_{E,p} = -1/\beta$ and $\varepsilon_{E,K} = -1 + 1/\beta$.

Concerning the aggregate analysis, the following lemma proved in Appendix A.6 turns out to be useful:

Lemma 3 (Aggregate Effect of \underline{K} on $(\check{E} - \underline{E})/\underline{E}$ with an Isoelastic Benefit Function). *For $\underline{K} = K^\circ$, we have $\frac{\check{E} - \underline{E}}{\underline{E}} = -\varepsilon_{E,K}$; otherwise, $\frac{\check{E} - \underline{E}}{\underline{E}} > -\varepsilon_{E,K}$. We always have $\frac{d}{d\underline{K}} \frac{\check{E} - \underline{E}}{\underline{E}} > 0$ with $\lim_{\underline{K} \rightarrow \infty} \frac{\check{E} - \underline{E}}{\underline{E}} = \infty$.*

Thus, for introducing a weak standard, an indifferent household's additional energy consumption when deciding against an investment is as high as its additional energy savings if it still invests, whereas the former exceeds the latter for a strong standard.

We can now fully characterize the effects of a weak standard. Using $\varepsilon_{\check{K},\underline{K}} = 0$ and $(\check{E} - \underline{E})/\underline{E} = -\varepsilon_{E,K}$ for $\underline{K} = K^\circ$ from Lemma 1 and Lemma 3 in (3.5) yields

$$\Omega_{h,\underline{K}}(K^\circ) = \frac{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right]}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E} - \underline{E}}{\underline{E}}} \in \left[0, \frac{1}{\eta} \right], \quad (3.8a)$$

¹⁰For the proofs of our results, we use the more general isoelastic benefit function $B(K_i, E_i) \equiv b \frac{K_i^{1-\kappa} E_i^{1-\epsilon} - 1}{1-\beta}$ with $\kappa > 1, \epsilon > 1$ in the Appendix.

$$\Omega_{p,\underline{K}}(K^\circ) = \frac{\eta \varepsilon_{E,K}}{\chi(\underline{K}) [\theta - \varepsilon_{E,p}] [\eta - \check{\gamma} \varepsilon_{\check{K},h}] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E} - \underline{E}}{\underline{E}}} \in \left[\frac{\varepsilon_{E,K}}{\chi(\underline{K}) [\theta - \varepsilon_{E,p}]}, 0 \right]. \quad (3.8b)$$

Inspection of (3.8) allows us to complete Proposition 1:

Proposition 2 (The Effects of a Weak Minimum-Efficiency Standard with an Isoelastic Benefit Function). *Suppose $\underline{K} = K^\circ$ and $\check{\gamma} \in (0, \infty)$. Then:*

- 1.) *For $\eta \rightarrow \infty$, we have $\Omega_{h,\underline{K}} = 0$, $\Omega_{p,\underline{K}} \leq 0$, $\Omega_{k,\underline{K}} \in (0, 1]$ and $\Omega_{e,\underline{K}} \in (\varepsilon_{E,K}, 0]$, where $\Omega_{p,\underline{K}} = 0 \iff \theta \rightarrow \infty$, $\Omega_{k,\underline{K}} = 1 \iff \theta \rightarrow \infty$ and $\Omega_{e,\underline{K}} = 0 \iff \theta = 0$.*
- 2.) *For $\eta \in (0, \infty)$, we have $\Omega_{h,\underline{K}} > 0$, $\Omega_{p,\underline{K}} \leq 0$, $\Omega_{k,\underline{K}} \in (0, 1)$ and $\Omega_{e,\underline{K}} \in (\varepsilon_{E,K}, 0]$, where $\Omega_{p,\underline{K}} = 0 \iff \theta \rightarrow \infty$ and $\Omega_{e,\underline{K}} = 0 \iff \theta = 0$.*
- 3.) *For $\eta = 0$, we have $\Omega_{h,\underline{K}} > 0$ and $\Omega_{p,\underline{K}} = \Omega_{k,\underline{K}} = \Omega_{e,\underline{K}} = 0$.*

For $\eta \in (0, \infty)$ and $\theta \in (0, \infty)$, we thus find that a weak standard will do what one would expect it to do, namely to increase demand for efficiency capital, thereby driving up its price and reducing the investing households' energy demand. As this depresses the energy price, non-investing households consume more. In sum, a one-percent increase in the standard increases aggregate investment by less than one percent and reduces aggregate energy consumption by less than it directly reduces the energy consumption of the investing households. However, a weak standard does not backfire.

3.3 The Effects of a Strong Minimum-Efficiency Standard

We now extend the analysis to a *strong* minimum-efficiency standard. The following lemma proved in Appendix A.7 turns out to be useful:

Lemma 4 (Aggregate Effect of \underline{K} on \check{K} with an Isoelastic Benefit Function). *We always have $\frac{d|\varepsilon_{\check{K},K}|}{d\underline{K}} > \frac{d|\varepsilon_{\check{K},h}|}{d\underline{K}} > \frac{d\varepsilon_{\check{K},p}}{d\underline{K}} > 0$. Furthermore, $\frac{d\chi(\underline{K})}{d\underline{K}} > 0$ with $\lim_{\underline{K} \rightarrow \infty} \chi(\underline{K}) = \infty$. For $\underline{K} = K^\circ$, $\eta \rightarrow \infty$, $\theta \rightarrow \infty$ or $\check{\gamma} = 0$, we have $\frac{d[e - G(\check{K})\underline{E}]}{d\underline{K}} = 0$; otherwise, $\frac{d[e - G(\check{K})\underline{E}]}{d\underline{K}} > 0$. Furthermore, for $\eta > 0$ and $\theta > 0$, we have $\Omega_{k,\underline{K}} = \eta \Omega_{h,\underline{K}} > 0$ or $\Omega_{e,\underline{K}} = \theta \Omega_{p,\underline{K}} > 0$ or both. Finally, $\lim_{\underline{K} \rightarrow \infty} \check{K} = 0$ for $\eta \in [0, \infty)$, and $\lim_{\underline{K} \rightarrow \infty} \underline{E} = 0$.*

Thus, regardless of its current level, tightening the standard makes the cutoff level \check{K} more sensitive to changes in the standard and prices. Furthermore, we have $1/\chi(\underline{K}) = G(\check{K})\underline{E}/e$ for share of energy consumed by the investing households, and this share is decreasing in the standard (Lemma 2). Moreover, the non-investing households consume more energy even if the energy price rises, because the larger number of non-investing households outweighs the demand-dampening effect of the price increase. Furthermore, any stricter standard either increases aggregate investment and the capital price, or it increases aggregate energy consumption and the energy price. Finally, the cutoff level \check{K} and an investing household's energy consumption \underline{E} go to zero as the standard \underline{K} goes to infinity.

To further analyze how a minimum-efficiency standard affects the energy market and the efficiency-capital market, we make the following assumption throughout:

Assumption 2 (Cost and Distribution Functions). The cost functions are isoelastic:

$$C_k(k) \equiv c_k k^{\frac{1+\eta}{\eta}}, \quad C_e(e) \equiv c_e e^{\frac{1+\theta}{\theta}}, \quad (3.9)$$

where $c_k, c_e, \eta, \theta > 0$. The elasticity of the distribution function is weakly decreasing: $\gamma'(K) \leq 0$.

Isoelastic cost functions imply that the price elasticities of supply from (3.4) are constant. Furthermore, we assume $\gamma'(K) \leq 0$, i.e. the elasticity $\gamma(K)$ of the share $G(K)$ of households with capital below K is weakly decreasing.¹¹

We can now fully characterize the effects of a strong standard. Using $(\check{E} - \underline{E})/\underline{E} \geq -\varepsilon_{E,K}$ from Lemma 3 in (3.5) yields

$$\Omega_{h,\underline{K}}(\underline{K}) = \frac{\chi(\underline{K}) [\theta - \varepsilon_{E,p}] \left[1 + \check{\gamma} \varepsilon_{\check{K},\underline{K}} \right] + \overbrace{\check{\gamma} \varepsilon_{\check{K},p} \left[\varepsilon_{E,K} + \frac{\check{E} - \underline{E}}{\underline{E}} \right]}^{\geq 0}}{\chi(\underline{K}) [\theta - \varepsilon_{E,p}] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E} - \underline{E}}{\underline{E}}} \in \left(-1, \frac{1}{\eta} \right], \quad (3.10a)$$

$$\Omega_{p,\underline{K}}(\underline{K}) = \frac{\eta \left[\varepsilon_{E,K} - \check{\gamma} \varepsilon_{\check{K},\underline{K}} \frac{\check{E} - \underline{E}}{\underline{E}} \right] + \overbrace{-\check{\gamma} \varepsilon_{\check{K},h} \left[\varepsilon_{E,K} + \frac{\check{E} - \underline{E}}{\underline{E}} \right]}^{\geq 0}}{\chi(\underline{K}) [\theta - \varepsilon_{E,p}] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E} - \underline{E}}{\underline{E}}} \geq \frac{\varepsilon_{E,K}}{\chi(\underline{K}) [\theta - \varepsilon_{E,p}]}. \quad (3.10b)$$

In Appendix A.8, we then prove:¹²

Proposition 3 (The Effects of a Strong Minimum-Efficiency Standard with Isoelastic Benefit and Cost Functions). *If $\gamma(0) \leq |\varepsilon_{E,K}|$, then increasing \underline{K} always increases aggregate investment. By contrast, if $\gamma(0) > |\varepsilon_{E,K}|$, then aggregate investment initially increases in \underline{K} , but has a maximum at a critical value $\underline{K} = \underline{K}_k > 0$ and then decreases for higher values of \underline{K} . Aggregate energy consumption initially decreases in \underline{K} , but has a minimum at a critical value $\underline{K} = \underline{K}_e \in (0, \underline{K}_k)$ and then increases for higher values of \underline{K} . Finally, aggregate energy consumption is higher for $\underline{K} \rightarrow \infty$ than without a binding standard.*

The proposition firstly states that while a weak standard increases aggregate demand for efficiency capital, this effect diminishes as the standard becomes stricter, and *may* even be reversed when the standard is very strict. Consider the numerator of $\Omega_{h,\underline{K}}(\underline{K})$ in (3.10a). The second summand reflects how the change in the energy price, which is induced by the intensive and extensive margin effects, shifts \check{K} : A higher energy price means that more households want to invest (and vice versa). The term $1 + \check{\gamma} \varepsilon_{\check{K},\underline{K}}$ in the first summand summarizes

¹¹This assumption is satisfied for, e.g., the logistic distribution $G(K) = \frac{1}{1+e^{-x(K-\bar{K})}}$, the exponential distribution $G(K) = 1 - e^{-x(K-K_{\min})}$, the logarithmic distribution $G(K) = \left[\frac{\ln(1+K-K_{\min})}{\ln(1+K_{\max}-K_{\min})} \right]^x$, the isoelastic distribution $G(K) = \left(\frac{K}{K_{\max}} \right)^{\check{\gamma}}$ and the uniform distribution $G(K) = \frac{K-K_{\min}}{K_{\max}-K_{\min}}$, where $x > 0$ is a constant, and $K_{\min} \geq 0$, $\bar{K} \geq K_{\min}$ and $K_{\max} \geq \bar{K}$ are the smallest, mean and largest amounts of capital in the population.

¹²For $\gamma(0) \leq |\varepsilon_{E,K}|$, the supply elasticities being characterized by $\eta'(h) \leq 0$ and $\theta'(p) \gtrless 0$ with $\eta, \theta > 0$ is sufficient for the proposition to hold.

the direct effect on the demand for efficiency capital, namely that increasing \underline{K} increases investment of the households that still invest, but also deters more households from investing. If $\gamma(0) > |\varepsilon_{E,K}|$, this deterrence dominates for high levels of \underline{K} , such that increasing \underline{K} beyond a critical level reduces capital demand. Intuitively, if γ is high, a stricter standard will induce many households to stop investing, and if $|\varepsilon_{E,K}|$ is low, those households that continue to invest will not reduce their energy consumption much. By contrast, if $\gamma(0) \leq |\varepsilon_{E,K}|$, then increasing \underline{K} always increases capital demand.

Secondly, the proposition shows that even if the minimum-efficiency standard stimulates demand for efficiency capital, the effects on energy demand may be less promising. Consider the numerator of $\Omega_{p,\underline{K}}(\underline{K})$ in (3.10b). The second summand shows that an increase in the capital price reduces the share of investing households (and vice versa) and thereby has the above-mentioned effects on the energy market at the intensive and extensive margins. The first summand again summarizes the (more) direct effects of \underline{K} . Energy consumption of the marginal (and still investing) household is reduced, and households are kept from investing, such that their energy consumption increases. We can see that introducing a minimum-efficiency standard initially reduces aggregate energy demand, but there will be a level of \underline{K} minimizing it, and further increases in the standard increase energy consumption. More and more households are deterred from investing ($d|\varepsilon_{\check{K},\underline{K}}|/\underline{K} > 0$), such that energy consumption is minimized at $\underline{K} = \underline{K}_e$. Further increases in \underline{K} then increase aggregate energy consumption – that is, a sufficiently strong standard backfires.

The critical value \underline{K}_e is defined by (see Appendix A.9)

$$\frac{\underline{K}_e}{\check{K}} = \left\{ 1 + \frac{|\varepsilon_{E,K}|}{2} \left[1 + \frac{\eta|\varepsilon_{E,K}|}{\check{\gamma}(1+\eta)} + \sqrt{\left(1 + \frac{\eta|\varepsilon_{E,K}|}{\check{\gamma}(1+\eta)} \right)^2 + \frac{4\eta}{\check{\gamma}(1+\eta)}} \right] \right\}^{\frac{1}{|\varepsilon_{E,K}|}} \geq 2, \quad (3.11)$$

where the right-hand side increases in η and decreases in $\check{\gamma}$ and $|\varepsilon_{E,K}|$.¹³ If the supply of efficiency capital is completely inelastic ($\eta \rightarrow 0$), the increased energy demand of households that stop investing outweighs the reduced energy demand of households that continue to invest (see Lemma 3). In that case, the critical value \underline{K}_e coincides with the unconstrained investment K° , and the standard will always *increase* aggregate energy consumption. This complements the insight from Proposition 2: an inelastic supply of efficiency capital not only means that a minimum-efficiency standard is *ineffective* in reducing energy demand, but we now see that it is actually *counterproductive*.

Thirdly, at the standard that minimizes energy consumption, aggregate investment is still increasing in \underline{K} . Thus, the observation of additional aggregate investment is not a sufficient indicator for a policy that is effective in reducing energy demand. Finally, note that with a sufficiently strict standard, i.e. $\underline{K} \rightarrow \infty$ with $\underline{E} \rightarrow 0$, only households with $K_{i,0} = 0$ and, thus, $E_i = 0$ might still invest. This clearly leads to a higher energy price and higher energy

¹³If $\check{\gamma}$ is very low, no investing household is deterred from investing, so that aggregate energy consumption decreases. If $|\varepsilon_{E,K}|$ is very low, the energy demand of households that no longer invest does not increase, so that aggregate energy consumption decreases.

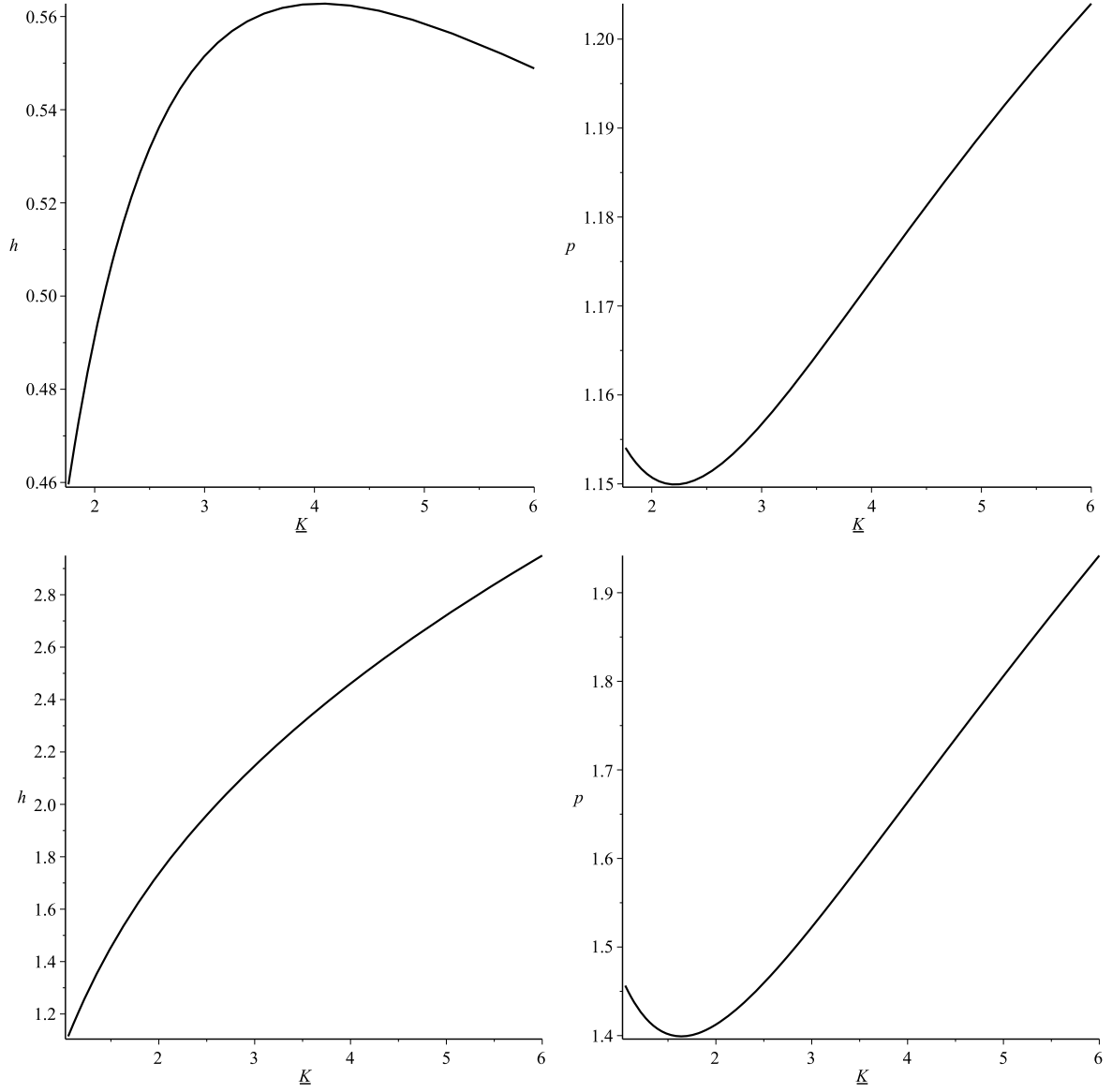


Figure 3: Effect of \underline{K} on h and p for $|\varepsilon_{E,p}| = |\varepsilon_{E,K}| = 1/2$, $b = c_k = c_e = \eta = \theta = 1$, $K_{\max} = 6$ and $\gamma = 1$ (upper panels) or $\gamma = 1/4$ (lower panels). The values at the intersection with the vertical axis correspond to the unconstrained investment case.

consumption than not having a standard at all.

Figure 3 illustrates the three main results of Proposition 3 with an isoelastic distribution function, i.e. $G(K) = (K/K_{\max})^\gamma$. In the upper panels, we see the effect of \underline{K} on h and p for $\gamma = 1 > |\varepsilon_{E,K}| = 1/2$. In this case, the capital price and, thus, aggregate investment increases with the standard for $\underline{K} < 4.2$, but decreases for $\underline{K} > 4.2$ and converges to zero. The energy price and, thus, aggregate energy consumption decreases with the standard for $\underline{K} < 2.2$, but increases for $\underline{K} > 2.2$ and exceeds the unconstrained energy consumption for $\underline{K} > 2.8$. In the lower panels, we have $\gamma = 1/4 < |\varepsilon_{E,K}| = 1/2$. In this case, the capital price always increases with the standard and goes to infinity. The energy price decreases with the standard for $\underline{K} < 1.6$, but increases for $\underline{K} > 1.6$ and exceeds the unconstrained energy consumption for $\underline{K} > 2.5$.

4 Adverse Effects of Minimum-Efficiency Standards

Proposition 3 reveals that a sufficiently strict minimum-efficiency standard leads to backfire. In particular, tightening a standard increases aggregate energy consumption if $\underline{K} \geq \underline{K}_e$, and implementing a sufficiently strict standard increases aggregate energy consumption compared to not having a standard at all. In contrast to an energy tax or an energy cap, a minimum-efficiency standard thus cannot enforce every desired level of aggregate energy consumption. In this section, we analyze the ways in which an effective minimum efficiency standard (i.e. $\underline{K} < \underline{K}_e$) nevertheless has adverse effects. In particular, we first analyze how effective such a standard is and then analyze what welfare implications it entails.

4.1 Rebound Effects

There is a large literature on the effect of energy efficiency on energy demand, and how the reduction of energy demand usually falls short of what might be expected based on the assumption that households keep their demand for energy services constant when energy efficiency increases. This difference is the *energy-efficiency rebound* R (Greening et al., 2000):

$$R = 1 - \frac{\text{actual marginal energy savings}}{\text{potential marginal energy savings}} = 1 - \frac{\text{actual elasticity of energy savings}}{\text{potential elasticity of energy savings}}. \quad (4.1)$$

In the literature, the analyzed energy-efficiency increases always take place at the intensive margin (i.e., they neglect the scrapping decision) and are usually exogenous and costless. However, our framework allows to analyze an *energy-efficiency policy rebound*. While the “savings” in the literature refer to the savings of an energy-efficiency increase, the “savings” in our framework would be the savings of an increase in the minimum-efficiency standard.

In our setting, the *actual elasticity of energy savings* is given by $\Omega_{e,\underline{K}}$. Backfire ($R > 1$) occurs if $\Omega_{e,\underline{K}} < 0$. We define the *potential energy savings* as the energy savings that would result if the prices of capital and energy did not change ($\eta, \theta \rightarrow \infty$), all investing households continued to invest ($\varepsilon_{\check{K},\underline{K}} = 0$), and all investing households consumed energy such that their demand for energy services did not change ($d\underline{S} = 0$). Then, the *potential elasticity of energy savings* is given by the share of energy consumed by the investing households, i.e. $-G(\check{K})\underline{E}/e$. In Appendix A.10, we derive

$$R = \underbrace{-\varepsilon_{E,p}}_{DE>0} - \underbrace{\check{\gamma}\varepsilon_{\check{K},\underline{K}}\frac{\check{E}-\underline{E}}{\underline{E}}}_{IE\geq 0} + \underbrace{CPE(\eta, \check{\gamma}) + EPE(\theta, \check{\gamma}) + RPE(\eta, \theta, \check{\gamma})}_{PE\geq 0}, \quad (4.2)$$

where the price effect (PE) is zero in case of perfectly elastic supply functions. In that case, the rebound effect consists of the direct effect (DE) and the investment effect (IE). A stricter minimum-efficiency standard increases the marginal benefit of energy consumption for households that still invest, such that they increase their energy services ($d\underline{S} > 0$) by diluting their energy savings. This DE is strong when the price elasticity of energy demand is large,

i.e. when households are sensitive to changes in the marginal benefit of energy consumption. The investment effect reflects that a stricter minimum-efficiency standard deters households from investing, i.e. the “scrap elasticity” $\check{\gamma}_{\varepsilon_{\check{K},\underline{K}}}$ represents the percentage by which the share of investing households decreases in response to a one percent increase in the standard, and that these households increase their energy consumption, i.e. $(\check{E} - \underline{E})/\underline{E}$. For a weak standard, the IE is zero.

If at least one of the supply functions is not perfectly elastic and there is no backfire, the PE is positive. A stricter minimum-efficiency standard increases the capital price and decreases the energy price, which reduces investment and increases energy consumption. The PE can be decomposed into the positive capital price effect (CPE), the positive energy price effect (EPE), and the negative residual price effect (RPE).¹⁴ Isolating the capital price effect and the energy price effect leads to an overestimation of their individual influences, which are partly driven by mutually reinforcing effects reflected by the residual price effect. For example, a stricter minimum-efficiency standard increases the capital price sharply if the supply of capital is relatively inelastic. However, the same happens if the supply of energy is relatively inelastic; in that case, the energy price also increases sharply when energy is used instead of capital, which then reduces substitution and further increases the capital price. In particular, we prove in Appendix A.11¹⁵

Lemma 5 (Effect of η, θ and $\check{\gamma}$ on R). *For $R < 1$, $\eta \in (0, \infty)$, $\theta \in (0, \infty)$ and $\check{\gamma} \in (0, \infty)$, we have $\frac{\partial R}{\partial \eta}, \frac{\partial R}{\partial \theta}, \frac{\partial^2 R}{\partial \eta \partial \theta} < 0$ and $\frac{\partial R}{\partial \check{\gamma}} > 0$.*

$\partial R / \partial \check{\gamma} > 0$ implies that the positive effect of $\check{\gamma}$ on the IE outweighs the potentially negative effect of $\check{\gamma}$ on the PE , and that $\check{\gamma}$ is also relevant in case of a weak minimum-efficiency standard. Furthermore, it allows us to derive a lower bound for the rebound effect given that there were no marginal (investing) household, i.e. $R|_{\check{\gamma}=0} = (\theta|\varepsilon_{E,p}| + |\varepsilon_{E,p}|) / (\theta + |\varepsilon_{E,p}|) < 1$. Finally, we prove in Appendix A.12¹⁶

Proposition 4 (The Effects of a Minimum-Efficiency Standard on the Rebound Effect). *Suppose $\check{\gamma} > 0$. A stricter standard increases the rebound effect.*

Proposition 4 reveals that estimating the rebound effect at the margin leads to an underestimation of the rebound effect for a stricter minimum-efficiency standard. To get a sense of how important it is to account for the altered investment decision of the marginal (investing) household and to distinguish between a weak and a strong minimum-efficiency standard, we estimate the rebound effect of the CAFE standard in the year 2017.¹⁷ This standard defines a minimum miles per gallon (mpg) for new cars.¹⁸ Thus, K_i are miles per gallon and $S_i = K_i E_i$ are miles driven.

¹⁴The CPE is zero if $\check{\gamma} = 0$, and the RPE is zero if $\eta \rightarrow \infty$ or $\theta \rightarrow \infty$ or $\check{\gamma} = 0$.

¹⁵For $R \leq 1$, we always have $\frac{\partial R}{\partial \eta}, \frac{\partial R}{\partial \theta}, \frac{\partial^2 R}{\partial \eta \partial \theta} \leq 0$ and $\frac{\partial R}{\partial \check{\gamma}} \geq 0$.

¹⁶The supply elasticities being characterized by $\eta'(h), \theta'(p) \leq 0$ with $\eta, \theta > 0$ is sufficient for the proposition to hold.

¹⁷The latest major (130,000 households) National Household Travel Survey was carried out in the year 2017 and provides the distribution of vehicle ages (FHWA, 2017).

¹⁸The CAFE standard sets the minimum average fuel economy of each manufacturer’s fleet. Since it has

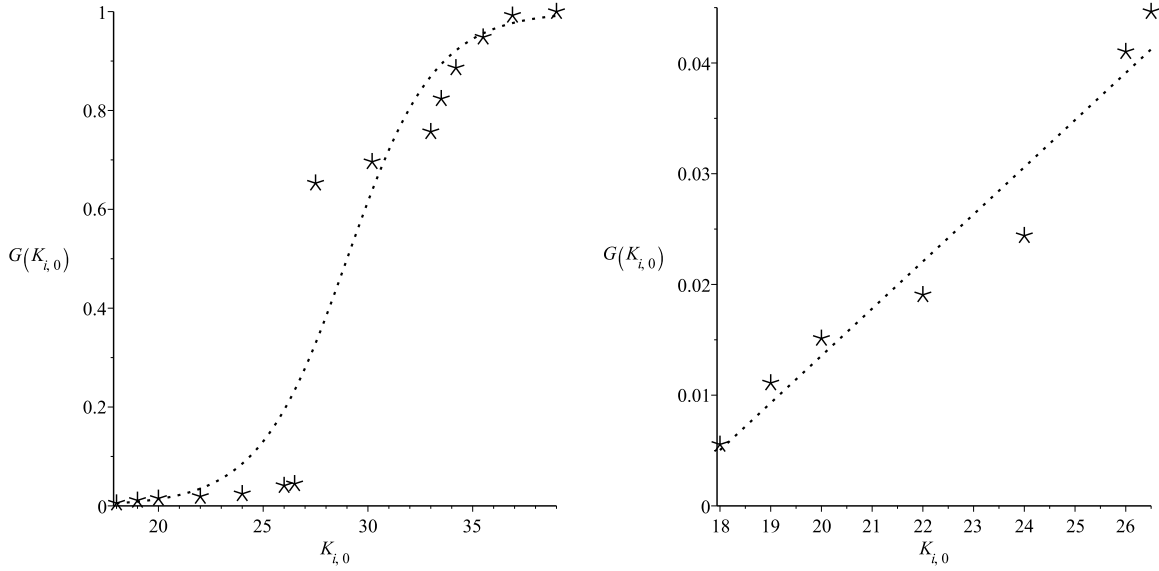


Figure 4: Distribution of the current passenger car fuel economy (asterisks), logistic approximation of the entire distribution (left panel, dotted curve), and uniform approximation of the distribution's lower tail (right panel, dotted curve).

For the price elasticity of car fuel demand, we then use $|\varepsilon_{E,p}| = 0.25$ from Labandeira et al. (2017, Tables 4 and 6) and Dimitropoulos et al. (2018). For the price elasticity of car fuel supply, we use $\theta = 1$ (cf. Böhringer and Rivers, 2021, p. 13). For the price elasticity of car fuel-economy supply (capital supply), we use $\eta = 1$ (cf. Greene and DeCicco, 2000, pp. 528–529 and Fullerton and Ta, 2020, p. 10). From the distribution of vehicle ages, the production share of passenger cars and the past CAFE standards (see Appendix A.13), the distribution of the current U.S. passenger car fuel economy is illustrated in Figure 4.¹⁹ The current standard is 39 mpg and the laxest standard was 18 mpg ($\underline{K}/\check{K} = 39/18$). The distribution can best be approximated by the logistic function $G(K) = 1/[1 + e^{-0.47(K-29.01)}]^{-1}$, which yields $\check{\gamma} = 8.48$, but the distribution at the lower tail can better be approximated by the uniform distribution $G(K) = (K - 16.8)/(252 - 16.8)$, which yields $\check{\gamma} = 15.21$ (see Appendix A.13). Finally, we use the actual distribution to derive the share of energy consumed by the investing households dependent on $|\varepsilon_{E,p}|$, which yields $1/\chi(\underline{K}) = G(\check{K})\underline{E}/e \in [0.56\%, 0.76\%]$ (see Appendix A.13).

With our central parameter values and the uniform distribution, i.e. $\varepsilon_{E,p} = |0.25|$, $\theta = 1$, $\eta = 1$, $\check{\gamma} = 15.21$, we get a rebound effect of $R = 99\%$. Decomposing this effect yields $DE = 25\%$, $IE = 32\%$, $CPE = 42\%$, $EPE = 9\%$ and $RPE = -9\%$. If the altered investment decision of the marginal (investing) household were not taken into account, the calculated rebound effect would only be $R|_{\check{\gamma}=0} = 40\%$ with $DE = 25\%$ and $EPE = 15\%$. Thus, the

been binding for all manufacturers for several years (Dou and Linn, 2020), we abstract from manufacturer heterogeneity. Furthermore, we follow the literature in aggregating vehicle types and also abstract from vehicle heterogeneity (see, e.g., Goulder et al., 2012; Jacobsen and van Benthem, 2015; Bento et al., 2018; Dou and Linn, 2020).

¹⁹For example, the distribution $G(18) = 0.56\%$ reflects the current share of passenger cars from the production year 1978 with a standard of 18 mpg. The huge difference between the distribution $G(26.5) = 4.46\%$ and the distribution $G(27.5) = 65.28\%$ stems from the fact that the standard was 27.5 mpg for the 22 production years between 1989 and 2010, such that the share of passenger cars with a standard of 27.5 mpg is $65.28\% - 4.46\% = 60.82\%$.

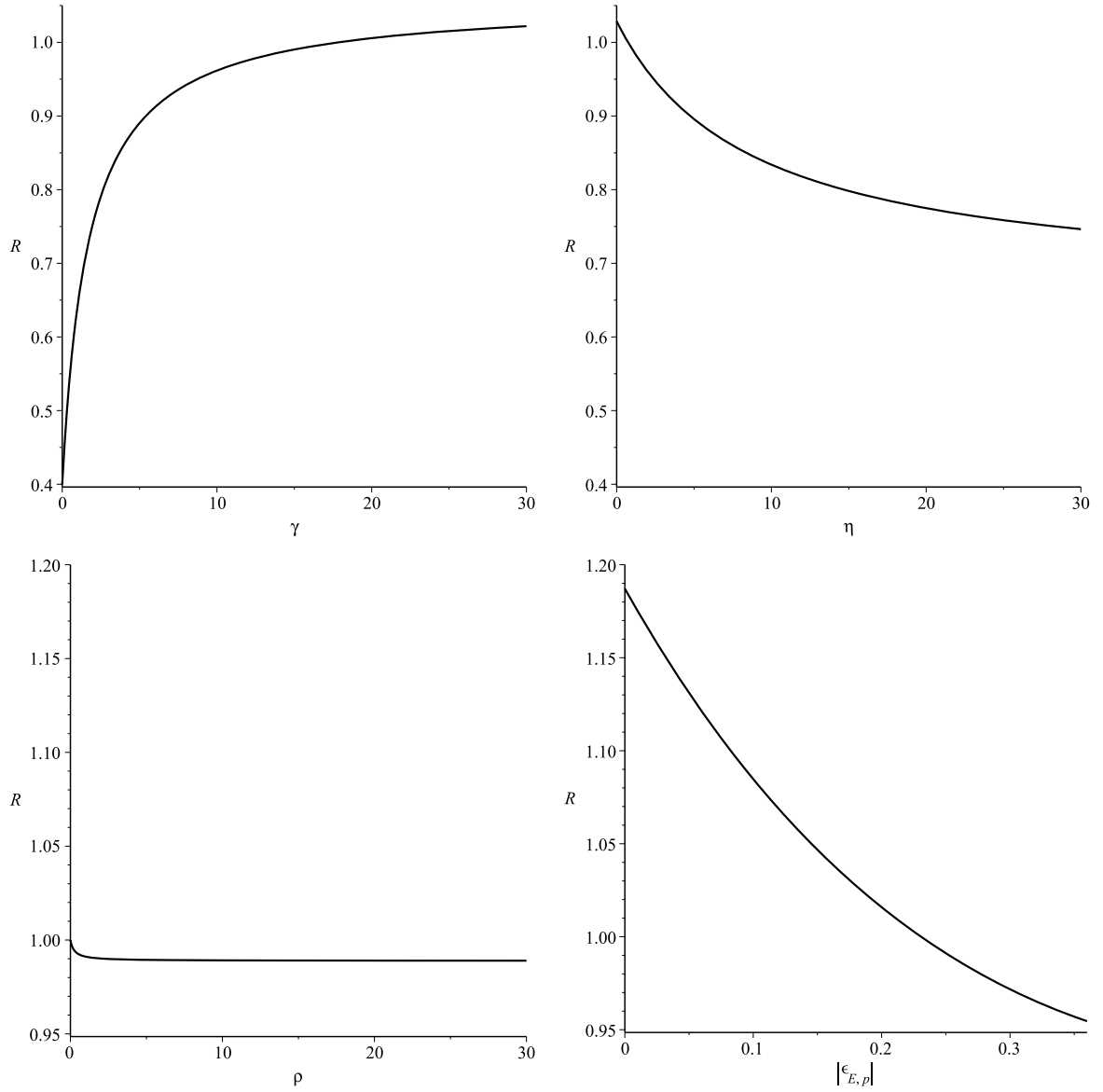


Figure 5: Sensitivity analysis for the uniform distribution ($\check{\gamma} = 15.21$)

very strong rebound effect of $R = 99\%$ is driven by the investment decision of the marginal (investing) household, with a huge effect of both, the *IE* via reduced benefits of investment and the *CPE* via an increased capital price. The huge effect of $\check{\gamma}$ on the rebound effect can also be seen in Figure 5, where selected parameters are changed while all other parameters remain constant. In accordance with Lemma 5, the rebound effect increases with $\check{\gamma}$ and decreases with η and θ . However, increasing $\check{\gamma}$ from 0 to 30 increases the rebound effect from $R = 40\%$ to $R = 102\%$, while increasing η [θ] from 0 to 30 reduces the rebound effect only from $R = 103\%$ to $R = 75\%$ [$R = 100\%$ to $R = 99\%$]. Interestingly, the rebound effect decreases with $|\varepsilon_{E,p}|$, suggesting that the *DE* is not the driving force behind it.²⁰

Applying the logistic distribution instead of the uniform distribution, i.e. $|\varepsilon_{E,p}| = 0.25, \theta = 1, \eta = 1, \check{\gamma} = 8.48$, we still get a rebound effect of $R = 95\%$. Decomposing this effect yields $DE = 25\%$, $IE = 18\%$, $CPE = 51\%$, $EPE = 12\%$ and $RPE = -11\%$. Thus, the smaller *IE* is partially compensated by the larger *PE*.

²⁰The minimum-efficiency standard becomes non-binding for $|\varepsilon_{E,p}| > 0.36$.

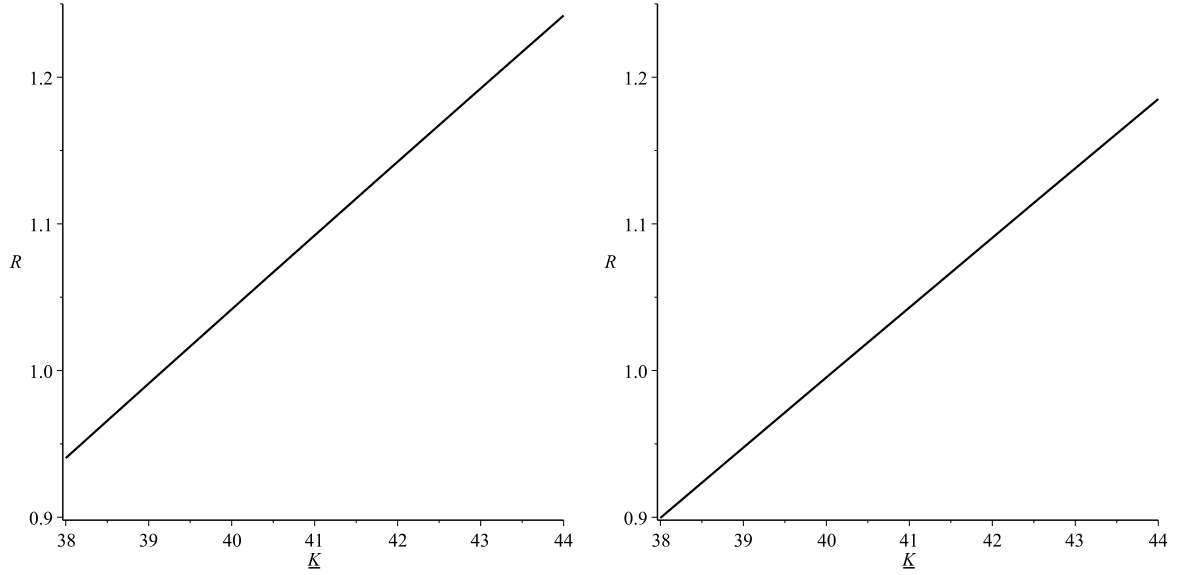


Figure 6: Different standards for the uniform distribution ($\check{\gamma} = 15.21$, left panel) and the logistic distribution ($\check{\gamma} = 8.48$, right panel)

Finally, to get a sense of how important it is to distinguish between a weak and a strong minimum-efficiency standard, we vary \underline{K} in Figure 6 and approximate $\check{\gamma}$ and the share of energy consumed by the investing households to be constant.²¹ For $\underline{K} < 38$, the minimum-efficiency standard becomes non-binding. If $\underline{K} = 38$, the rebound effect is $R = 94\%$ and $R = 90\%$ for $\check{\gamma} = 15.21$ and $\check{\gamma} = 8.48$, respectively. If $\underline{K} > 39.2$ and $\underline{K} > 40.1$, there is backfire for $\check{\gamma} = 15.21$ and $\check{\gamma} = 8.48$, respectively. Thus, the stringency of the minimum-efficiency standard is important for the rebound effect, but to account for the altered investment decision of the marginal (investing) household tends to be even more important, since this increases the rebound effect at least from $R|_{\check{\gamma}=0} = 40\%$ to $R = 94\%$ and $R = 90\%$ for $\check{\gamma} = 15.21$ and $\check{\gamma} = 8.48$, respectively.

4.2 Welfare Effects

We now turn to the question of how the minimum-efficiency standard affects the welfare of different households and firms, and how this compares to other policy instruments. There are three kinds of households: Those who invest despite the standard, $K_{i,0} < \check{K}$, those who would have invested only without the standard, $K_{i,0} \in [\check{K}, \tilde{K})$, and those who would not have invested in any case, $K_{i,0} \geq \tilde{K}$. Using (2.2), (2.3) and Proposition 3, we see that the latter two groups – i.e. the non-investing households – benefit from a stricter standard if and only if it reduces the energy price:

$$\frac{du_{i,0}}{d\underline{K}} = \underbrace{\left[\frac{\partial B_{i,0}}{\partial E} - p \right]}_{=0} \frac{dE_{i,0}}{d\underline{K}} - \frac{dp}{d\underline{K}} E_{i,0} = -\Omega_{p,\underline{K}} \frac{pE_{i,0}}{\underline{K}} \gtrless 0 \text{ for } \underline{K} \gtrless \underline{K}_e. \quad (4.3)$$

²¹ $\check{\gamma} = g(\check{K})\check{K}/G(\check{K}) [G(\check{K})\underline{E}/e]$ tends to decrease [increase] with \underline{K} , because $G(\check{K})$ increases with \underline{K} . Thus, we tend to underestimate [overestimate] the rebound effect for less strict [stricter] standards than the current standard of $\underline{K} = 39$.

Using (2.2), (2.3), (2.13) and Proposition 3, consumption utility of the investing households develops by:

$$\begin{aligned}\frac{d\underline{u}}{d\underline{K}} &= \underbrace{\left[\frac{\partial \underline{B}}{\partial \underline{E}} - p\right]}_{=0} \frac{d\underline{E}}{d\underline{K}} - \frac{dp}{d\underline{K}} \underline{E} + \underbrace{\left[\frac{\partial \underline{B}}{\partial \underline{K}} - h\right]}_{\leq 0} \frac{d\underline{h}}{d\underline{K}} \underline{K} \\ &= -\Omega_{p,\underline{K}} \frac{p\underline{E}}{\underline{K}} - [h\underline{K} - p\underline{E}] \frac{1}{\underline{K}} - \Omega_{h,\underline{K}} h \gtrless 0 \text{ for } \underline{K} \gtrless \underline{K}_u \text{ with } \underline{K}_u < \underline{K}_e.\end{aligned}\quad (4.4)$$

Like the non-investing households, the investing households can benefit from reduced energy prices. Additionally, they benefit from reduced capital prices for $\underline{K} > \underline{K}_k$. However, a stricter standard implies a larger gap between the expenditures for capital and energy, and for the isoelastic benefit function, this effect outweighs the benefit from (potentially) reduced capital prices. In particular, there is a critical value $\underline{K}_u \in [0, \underline{K}_e)$ above which the investing households suffer from a stricter standard. Note that $\frac{d\underline{u}_{i,0}}{d\underline{K}} \leq 0$ for $\underline{K} \geq \underline{K}_e$ and $\frac{d\underline{u}}{d\underline{K}} < 0$ for $\underline{K} > \underline{K}_u$ imply that there is also a critical value $\underline{K}_u \in [\underline{K}_u, \underline{K}_e]$ above which the households suffer on average from a stricter standard.

To determine the effect of the minimum-efficiency standard on profits, note that the equilibrium lies on the aggregate supply curves due to perfect competition. Accordingly, the firms' profit increases if and only if the respective price increases. Since a stricter standard either increases the capital price or the energy price or both, at least one sector's profit increases, and total profits definitely increase for $\underline{K} \in (\underline{K}_e, \underline{K}_k)$. Formally, using (3.2) and Proposition 3, we have:

$$\frac{d\pi_k}{d\underline{K}} = \underbrace{[h - C'_k]}_{=0} \frac{d\underline{k}}{d\underline{K}} + \frac{dh}{d\underline{K}} \underline{k} = \Omega_{h,\underline{K}} \frac{h\underline{k}}{\underline{K}} \gtrless 0 \text{ for } \underline{K} \gtrless \underline{K}_k, \quad (4.5a)$$

$$\frac{d\pi_e}{d\underline{K}} = \underbrace{[p - C'_e]}_{=0} \frac{d\underline{e}}{d\underline{K}} + \frac{dp}{d\underline{K}} \underline{e} = \Omega_{p,\underline{K}} \frac{p\underline{e}}{\underline{K}} \gtrless 0 \text{ for } \underline{K} \gtrless \underline{K}_e. \quad (4.5b)$$

Finally, let us define total welfare by:

$$w = \int_0^{\check{K}} \lambda(K_{i,0}) g(K_{i,0}) \underline{u} dK_{i,0} + \int_{\check{K}}^{\infty} \lambda(K_{i,0}) g(K_{i,0}) \underline{u}_{i,0} dK_{i,0} + \lambda_k \pi_k + \lambda_e \pi_e, \quad (4.6)$$

where $\lambda(K)$ is the welfare weight of a household's consumption utility, which may depend on its capital endowment, and λ_k and λ_e is the welfare weight of the capital firm's profit and the energy firm's profit, respectively. From (4.3)-(4.6), total welfare depends on the minimum-efficiency standard as follows:

$$\begin{aligned}\frac{dw}{d\underline{K}} &= \int_0^{\check{K}} \lambda(K_{i,0}) g(K_{i,0}) \left[\frac{\partial \underline{B}}{\partial \underline{K}} - h - \Omega_{h,\underline{K}} h \right] dK_{i,0} \\ &\quad - \int_0^{\infty} \lambda(K_{i,0}) g(K_{i,0}) \Omega_{p,\underline{K}} \frac{p\underline{E}_i}{\underline{K}} dK_{i,0} + \lambda_k \Omega_{h,\underline{K}} \frac{h\underline{k}}{\underline{K}} + \lambda_e \Omega_{p,\underline{K}} \frac{p\underline{e}}{\underline{K}},\end{aligned}\quad (4.7)$$

which implies

$$\left. \frac{dw}{d\bar{K}} \right|_{\lambda(K)=\lambda} = -\lambda [h\bar{K} - p\bar{E}] \frac{G(\bar{K})}{\bar{K}} - [\lambda - \lambda_k] \Omega_{h,\bar{K}} \frac{hk}{\bar{K}} - [\lambda - \lambda_e] \Omega_{p,\bar{K}} \frac{pe}{\bar{K}}. \quad (4.8)$$

We characterize the welfare effects in the following proposition (see Appendix A.14):

Proposition 5 (The Effects of a Minimum-Efficiency Standard on Utility, Profits and Welfare). *Suppose $\eta \in [0, \infty)$, $\theta \in [0, \infty)$ and $\check{\gamma} \in [0, \infty)$. A stricter standard increases consumption utility of the non-investing households if and only if $\bar{K} < \bar{K}_e$ and increases consumption utility of the investing households if and only if $\bar{K} < \bar{K}_u (< \bar{K}_e)$. Furthermore, it increases the capital firm's profit if and only if $\bar{K} < \bar{K}_k$ and reduces the energy firm's profit if and only if $\bar{K} < \bar{K}_e (< \bar{K}_k)$. A weak standard reduces total consumption utility and increases total profits if and only if $\eta < \frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|}$. A stricter standard reduces total consumption utility if $\eta \leq \frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|}$ and increases total profits if $\eta \leq \frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|}$ and $\gamma(0) \leq |\varepsilon_{E,K}|$ or $\eta \in \left[\frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|} - 1, \frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|} \right]$. Finally, it reduces the total unweighted utilitarian welfare of the economy, i.e. the value of w for $\lambda = \lambda_k = \lambda_e$.*

The households benefit on average from a weak standard if the capital-supply elasticity is high enough (relative to the energy-supply elasticity and the energy-demand elasticity) and suffer from a stricter standard in the opposite case.²² Since there is no market failure in the model, total profits can only increase if total consumption utility decreases. However, the households suffering from a stricter standard is not sufficient for the firms to gain; for this, the capital-supply elasticity must be low enough to increase the price sufficiently and capital demand must not decrease too much in the standard. The latter condition is fulfilled if $\gamma(0) \leq |\varepsilon_{E,K}|$, such that capital demand increases in the standard, or if $\eta \geq \frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|} - 1$, such that the capital-supply elasticity is high enough to stabilize the demand sufficiently.

With our central parameter values from the last subsection, i.e. $\varepsilon_{E,p} = |0.25|$, $\theta = 1$, $\eta = 1$, $\check{\gamma} = 15.21$, the condition $\eta \in \left[\frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|} - 1, \frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|} \right]$ is fulfilled, such that total consumption utility decreases and total profits increase in the standard. Normalizing $\lambda_k = \lambda_e = 1$ and approximating $\check{\gamma}$ and the share of energy consumed by the investing households to be constant, Figure 7 visualizes which welfare-maximizing standard can be explained by which relative welfare weight of the households' consumption utility. For instance, the current standard of 39 mpg can be explained by $\mu = 0.52$, and a non-binding standard of < 38 mpg can be explained by $\mu = 1$.

Without market failures such as pollution externalities or information problems, any minimum-efficiency standard reduces total welfare if $\lambda = \lambda_k = \lambda_e$. Then, the welfare loss is proportional to the gap between capital and energy expenditures of the investing households, see (4.8). Thus, a stricter standard only makes sense if there are market failures or if the welfare weights differ. In the latter case, the preference for a stricter standard requires sufficiently high welfare weights for the non-investing households or for the capital firms if $\bar{K} \leq \bar{K}_e$, and

²²A stricter standard does not significantly increase the capital price if η is high, and it significantly reduces the energy price if θ and $|\varepsilon_{E,p}|$ are low.

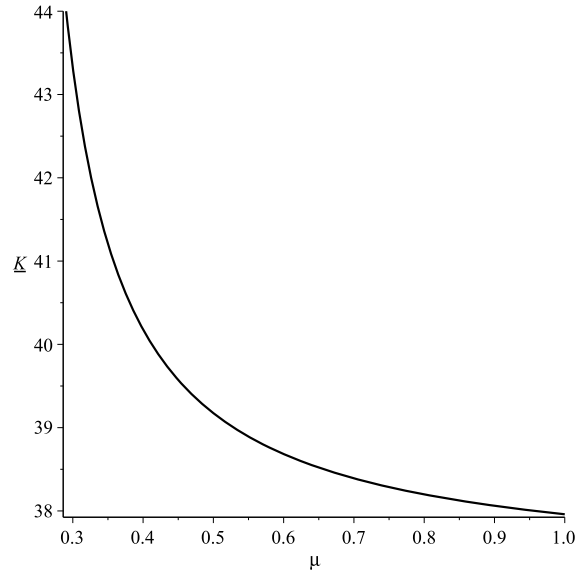


Figure 7: Welfare-maximizing standard depending on the relative welfare weight of the households' consumption utility.

sufficiently high welfare weights for the energy firms or the capital firms if $\underline{K}_e \leq \underline{K} \leq \underline{K}_k$, and a sufficiently high welfare weight for the energy firms for any stricter standard. However, energy consumption and capital investment are typically accompanied by market failures. In order to be able to better classify the welfare effects of the minimum-efficiency standard in this case, we integrate an energy supply tax and a capital supply subsidy into our model in Appendix A.15.

First, suppose that energy production (or consumption) is associated with pollution, which argues for an energy tax to efficiently internalize this externality. A higher energy tax always increases the energy price and reduces aggregate energy consumption, and it always increases the capital price and aggregate investment if $\theta > 0$ and $\eta \in (0, \infty)$: As energy becomes scarcer, households replace energy with capital, which increases capital scarcity. Thus, the effects on prices and quantities are unambiguous in case of an energy tax, whereas they are reversed at \underline{K}_e and \underline{K}_k in case of a minimum-efficiency standard. Furthermore, both an energy tax and an effective minimum-efficiency standard ($\underline{K} < \underline{K}_e$) reduce aggregate energy consumption, and they increase the capital price and aggregate investment, but in contrast to the energy tax, the minimum-efficiency standard reduces the energy price.

Now let us compare a one-percent reduction in aggregate energy consumption induced by a stricter standard or by a higher tax. The preferences regarding a higher tax crucially depend on the distribution of the tax revenues. If these revenues are transferred to the energy firms, then the non-investing households prefer a stricter standard, because it reduces the energy price and increases their utility, whereas the higher tax increases the energy price and decreases their utility. By contrast, if the tax revenues are equally distributed to the households, then only those non-investing households that consume above-average energy prefer a stricter standard, whereas those that consume below-average energy prefer a higher tax. It turns out that the capital price increases less in case of a higher tax than in case of a stricter

standard.²³ Furthermore, a higher tax does not increase the gap between the capital price and the investing household's marginal benefit of capital. Consequently, investing households tend to prefer a higher tax, and they definitely do so if they consume below-average energy and the tax revenues are equally distributed to the households. However, if these revenues are transferred to the energy firms, investing households definitely suffer from the higher energy price and capital price induced by a higher tax, whereas they could gain from a lower energy price induced by a stricter standard, such that they then definitely prefer the stricter standard as long as $\underline{K} < \underline{K}_u$.

The capital firms always prefer a stricter standard because it increases the capital price more than a higher tax, which only indirectly induces higher capital investment. By contrast, the energy firms prefer a higher tax if they receive some of the tax revenues, whereas they are indifferent between the policies if they receive none. Then, it does not matter for them whether the one-percent reduction in aggregate energy consumption is induced by a stricter standard or by a higher tax, the change in the supply price and, thus, in the energy firms' profit will be the same. Concerning total welfare, a higher energy tax is beneficial if $\lambda = \lambda_k = \lambda_e$, since it does not increase the gap between the capital price and the investing household's marginal benefit of capital. A higher energy tax is also beneficial if $\lambda_e \geq \lambda \geq \lambda_k$, since the energy firms always (weakly) prefer the tax and the capital firms always prefer the standard. Consequently, using a standard instead of a tax to internalize a pollution externality can only be explained by sufficiently high welfare weights for the capital firms or for the non-investing households, provided that the tax revenues are distributed to the households and the non-investing households consume above-average energy.

Now suppose that households underestimate the benefits of investment due to information problems, which argues for a capital subsidy to increase investment.²⁴ A higher capital subsidy always reduces the capital price and increases the aggregate capital investment, and it always reduces the energy price and the aggregate energy consumption if $\eta > 0$ and $\theta \in (0, \infty)$: As capital becomes cheaper to them, households replace energy with capital, so their energy demand decreases. The differences to the minimum-efficiency standard are that the effects on prices and quantities are unambiguous in case of a capital subsidy, and that the minimum-efficiency standard increases the capital price.

Now let us compare a one-percent increase in aggregate investment induced by a stricter standard or by a higher subsidy. The preference for a higher subsidy crucially depends on the distribution of the subsidy costs. If these costs are financed by the capital firms, all households prefer a higher subsidy, because it decreases the energy price more than a stricter standard,²⁵

²³Intuitively, the increase in the tax does not have to be as large as the increase in the standard to induce a one-percent reduction in aggregate energy consumption, because the former reduces the energy demand of all households, whereas the latter increases the energy demand of the non-investing households. The large increase in the standard then implies a large increase in capital demand and, thus, in the capital price.

²⁴Alternatively, the households could underestimate the benefits of investment due to behavioral biases. Again, this argues for a capital subsidy to increase investment. Both, market failures (e.g. information problems) or behavioral biases could explain an energy-efficiency gap. See, for instance, Jaffe and Stavins (1994); Gillingham et al. (2009); Allcott and Greenstone (2012); Gillingham and Palmer (2014); Allcott (2016); Gerarden et al. (2017).

²⁵Intuitively, increasing the subsidy will encourage more households to invest (slightly more), while raising

it decreases the capital price, and it does not increase the gap between the capital price and the investing household's marginal benefit of capital. By contrast, if the subsidy costs are equally financed by the households, the investing households still prefer a higher capital subsidy because they invest above average, but the non-investing households may prefer a stricter standard to avoid the subsidy costs. However, on average the households still prefer a higher capital subsidy.

The capital firms prefer a stricter standard if they have to finance some of the subsidy costs, whereas they are indifferent between the policies if they do not have to finance any. Then, it does not matter for them whether the one-percent increase in aggregate investment is induced by a stricter standard or by a higher subsidy, the change in the supply price and, thus, in the capital firms' profit will be the same. By contrast, the energy firms always prefer a stricter standard because it decreases the energy price less than a higher subsidy. Concerning total welfare, a higher capital subsidy is beneficial if $\lambda = \lambda_k = \lambda_e$, since it does not increase the gap between the capital price and the investing household's marginal benefit of capital. A higher capital subsidy is also beneficial if $\lambda \geq \lambda_e, \lambda_k$, since the firms always (weakly) prefer the standard. Consequently, using a standard instead of a subsidy to increase investment can only be explained by sufficiently high welfare weights for the firms or maybe for the non-investing households, provided that the subsidy costs are financed by the households.

The key result of this section is that market failures (or behavioral biases) do not justify a minimum-efficiency standard if the policy goal is to maximize unweighted utilitarian welfare. However, the government may use this instrument to reduce energy consumption or to increase capital investment if it puts a higher welfare weight on the capital firms or the non-investing households. The former always prefer a minimum-efficiency standard to an energy tax or a capital subsidy, and the latter tend to do so. In general, different welfare weights for different groups may be due to the influence of interest groups (see e.g. Grossman and Helpman, 2001). Alternatively, they could reflect a certain understanding of fairness – in particular, non-investing households are often those that have recently invested, so the government may want to exempt them from a regulatory burden.²⁶

5 Conclusions

The present article analyzes the effects of a typical energy-efficiency policy – the introduction of a minimum-efficiency standard. This policy forces investing households to choose higher energy efficiency, but also makes investing less attractive. Therefore, a minimum-efficiency

the standard will encourage fewer households to invest (much more). In the first case, many households with relatively high energy consumption reduce their energy demand, in the second case a few households with relatively low energy consumption reduce their energy demand. Consequently, the energy price decreases more with a higher subsidy than with a stricter standard.

²⁶For the distributional consequences of a minimum-efficiency standard compared to a carbon tax depending on household income, see e.g. Jacobsen (2013); Davis and Knittel (2019); Levinson (2019); Zhao and Mattauch (2022). For a comparison of a second-best energy tax and a second-best energy-efficiency subsidy with a negative externality from energy consumption and a positive internalty from energy efficiency, see Chan and Globus-Harris (2023).

standard may have unintended consequences. Introducing a weak minimum-efficiency standard – that is, a standard that enforces energy efficiency barely above what households would choose on their own – has the consequences one would expect: Increased demand for efficiency capital and reduced energy demand. However, there is a critical value of the standard that minimizes energy demand, and increasing it further will increase energy demand, even though aggregate energy-efficiency investment still increases. Ultimately, a sufficiently strict standard will result in higher energy demand than not having a standard at all.

However, even if the standard is weak enough to reduce energy demand, its effectiveness is limited due to *rebound effects*. The literature on rebound effects generally analyzes the effects of exogenous energy-efficiency improvements. In contrast, the endogenous investment decision in our framework opens up a new rebound channel. In our central calibration of the CAFE standard, this investment effect accounts for one third of the total rebound effect and makes a stricter standard almost ineffective.

Furthermore, we analyze the distributional consequences of an effective standard. First, it benefits capital firms and harms energy firms because it raises the price of efficiency capital and lowers the energy price. Second, the investing households suffer from the former effect, while all households benefit from the latter. Consequently, total consumption utility decreases if the capital supply elasticity is sufficiently small (strong price increase) and the energy demand and supply elasticities are sufficiently large (weak price decrease). The dead-weight loss of the policy is proportional to the gap between capital and energy expenditures of the investing households.

Finally, we compare the distributional consequences of a one-percent reduction in energy demand through a standard with that of an energy tax. The reduction in the energy producer price is the same, while a standard increases the price of efficiency capital more than an energy tax. Consequently, the capital firms prefer the standard, while the energy firms prefer the tax if they receive some of the tax revenue. Since the energy tax increases the energy consumer price, the non-investing households prefer the standard if they receive no tax revenue, while the investing households tend to prefer the energy tax due to the less pronounced increase in the price of efficiency capital. If the households receive all tax revenue, on average they prefer the energy tax.

A standard causes a greater welfare loss than an energy tax. Therefore, a standard as a means of reducing energy demand only makes sense if the policymaker cares more about the profits of capital firms and non-investing households than about the profits of energy firms and other households, perhaps due to the influence of interest groups. Thus, further analyzing the political economy of energy-efficiency policy, and the choice of this environmental-policy instrument over others, is a valuable direction for future research. Our model predicts that households that have high-efficiency devices – like fuel-efficient cars, a refrigerator with a high efficiency class, an efficient space-heating system – favor minimum-efficiency standards. Households with old, inefficient devices should oppose such policies.

We also compare the distributional consequences of a one-percent increase in capital investment through a standard with those of a capital subsidy to close a potential energy effi-

ciency gap. Again, firms prefer the quantity instrument, households tend to prefer the price instrument, and the standard leads to greater welfare losses than the capital subsidy.

In our model, initial efficiency-capital endowments are exogenous, and households only invest for the current period. A valuable direction for future research is extending the model to a fully dynamic setting. Finally, we consider heterogeneity regarding the initial efficiency-capital endowments, but we abstract from heterogeneity regarding the benefits from energy services. Including this heterogeneity in the model could help empirical calibrations distinguish between different types of consumers, for example between young and old people. Finally, we show that an energy tax is superior to a standard for internalizing an environmental externality and that an energy-efficiency subsidy is superior to a standard for closing the energy efficiency gap. Further investigating the welfare effects of standards, energy taxes and capital subsidies in second-best situations is a promising avenue for further research.

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A Appendix

A.1 Individual Demand

For the general energy-services benefit function $B(K_i, E_i)$ with $\frac{\partial B_i}{\partial E} > 0$ and $\frac{\partial B_i}{\partial K} > 0$, we assume strict concavity, limit behavior that ensures internal solutions, and capital and energy being substitutes:

$$\frac{\partial^2 B_i}{\partial E^2} < 0, \quad \frac{\partial^2 B_i}{\partial K^2} < 0, \quad \frac{\partial^2 B_i}{\partial E^2} \frac{\partial^2 B_i}{\partial K^2} - \left[\frac{\partial^2 B_i}{\partial E \partial K} \right]^2 > 0, \quad (\text{A.1a})$$

$$\lim_{E_i \rightarrow 0} \frac{\partial B_i}{\partial E} \big|_{K_i \nearrow \infty} = \lim_{K_i \rightarrow 0} \frac{\partial B_i}{\partial K} \big|_{E_i \nearrow \infty} = \infty, \quad \lim_{E_i \rightarrow \infty} \frac{\partial B_i}{\partial E} \big|_{K_i > 0} = \lim_{K_i \rightarrow \infty} \frac{\partial B_i}{\partial K} \big|_{E_i > 0} = 0, \quad (\text{A.1b})$$

$$\frac{\partial^2 B_i}{\partial E \partial K} \big|_{E_i, K_i \nearrow \infty} = \frac{\partial^2 B_i}{\partial K \partial E} \big|_{E_i, K_i \nearrow \infty} < 0. \quad (\text{A.1c})$$

Then, the optimality conditions (2.3), (2.8) and (2.13) become

$$\frac{\partial B(K_i, E^*(K_i, p))}{\partial E} = p, \quad (\text{A.2a})$$

$$\frac{\partial B(K^\circ, E^*(K^\circ, p))}{\partial K} = h, \quad (\text{A.2b})$$

$$\frac{\partial B(\underline{K}, E^*(\underline{K}, p))}{\partial K} < h, \quad (\text{A.2c})$$

and the elasticities of energy demand (2.4) become

$$\varepsilon_{E,p}(K_i, p) \equiv \frac{\partial E_i^*(K_i, p) / E_i^*(K_i, p)}{\partial p / p} = \frac{1}{\frac{\partial^2 B(K_i, E^*(K_i, p))}{\partial E^2}} \frac{p}{E^*(K_i, p)} < 0, \quad (\text{A.3a})$$

$$\varepsilon_{E,K}(K_i, p) \equiv \frac{\partial E_i^*(K_i, p) / E_i^*(K_i, p)}{\partial K_i / K_i} = - \frac{\frac{\partial^2 B(K_i, E^*(K_i, p))}{\partial K \partial E}}{\frac{\partial^2 B(K_i, E^*(K_i, p))}{\partial E^2}} \frac{K_i}{E^*(K_i, p)} < 0. \quad (\text{A.3b})$$

Differentiating (2.7) for $I_i = hK_i$ and $B(S_i^*) = B(K_i, E^*(K_i, p))$, taking (A.2a) into account and making use of (A.3a) yields:

$$\frac{\partial U_i(K_i, p, hK_i)}{\partial K} = \frac{\partial B(K_i, E^*(K_i, p))}{\partial K} - h + \underbrace{\left[\frac{\partial B(K_i, E^*(K_i, p))}{\partial E} - p \right]}_{=0} \frac{\partial E^*(K_i, p)}{\partial K}, \quad (\text{A.4a})$$

$$\frac{\partial^2 U_i(K_i, p, hK_i)}{\partial K^2} = \frac{\frac{\partial^2 B(K_i, E^*(K_i, p))}{\partial K^2} \frac{\partial^2 B(K_i, E^*(K_i, p))}{\partial E^2} - \left[\frac{\partial^2 B(K_i, E^*(K_i, p))}{\partial K \partial E} \right]^2}{\frac{\partial^2 B(K_i, E^*(K_i, p))}{\partial E^2}} < 0. \quad (\text{A.4b})$$

By (A.1b), it is always worthwhile to buy at least some capital, i.e. $K^\circ > 0$. The optimal amount depends on the capital price h and the energy price p . Differentiating (A.2b) and

making use of (A.3) yields:

$$\frac{\partial^2 B^\circ}{\partial K^2} \frac{\partial K^\circ}{\partial h} + \frac{\partial^2 B^\circ}{\partial K \partial E} \frac{\partial E^\circ}{\partial K} \frac{\partial K^\circ}{\partial h} = 1 \Rightarrow \frac{\partial K^\circ}{\partial h} = \frac{\frac{\partial^2 B^\circ}{\partial E^2}}{\frac{\partial^2 B^\circ}{\partial E^2} \frac{\partial^2 B^\circ}{\partial K^2} - \left[\frac{\partial^2 B^\circ}{\partial K \partial E} \right]^2} < 0, \quad (\text{A.5a})$$

$$\frac{\partial^2 B^\circ}{\partial K^2} \frac{\partial K^\circ}{\partial p} + \frac{\partial^2 B^\circ}{\partial K \partial E} \left[\frac{\partial E^\circ}{\partial K} \frac{\partial K^\circ}{\partial p} + \frac{\partial E^\circ}{\partial p} \right] = 0 \Rightarrow \frac{\partial K^\circ}{\partial p} = - \frac{\frac{\partial^2 B^\circ}{\partial K \partial E}}{\frac{\partial^2 B^\circ}{\partial E^2} \frac{\partial^2 B^\circ}{\partial K^2} - \left[\frac{\partial^2 B^\circ}{\partial K \partial E} \right]^2} > 0. \quad (\text{A.5b})$$

Finally, differentiating (2.17) for $B(S_i^*) = B(K_i, E^*(K_i, p))$, taking $\frac{\partial K}{\partial h} = \frac{\partial K}{\partial p} = 0$ and (A.2a) into account and making use of (2.17) for $B(S_i^*) = B(K_i, E^*(K_i, p))$ yields

$$\begin{aligned} & \frac{\partial \underline{B}}{\partial \underline{K}} \frac{\partial \underline{K}}{\partial h} + \frac{\partial \underline{B}}{\partial \underline{E}} \frac{\partial \underline{E}}{\partial \underline{K}} \frac{\partial \underline{K}}{\partial h} - \left[\frac{\partial \check{B}}{\partial \underline{K}} \frac{\partial \check{K}}{\partial h} + \frac{\partial \check{B}}{\partial \underline{E}} \frac{\partial \check{E}}{\partial \underline{K}} \frac{\partial \check{K}}{\partial h} \right] - p \left[\frac{\partial \underline{E}}{\partial \underline{K}} \frac{\partial \underline{K}}{\partial h} - \frac{\partial \check{E}}{\partial \underline{K}} \frac{\partial \check{K}}{\partial h} \right] - h \frac{\partial \underline{K}}{\partial h} - \underline{K} = 0 \\ \Leftrightarrow & - \frac{\partial \check{B}}{\partial \underline{K}} \frac{\partial \check{K}}{\partial h} - \underline{K} = 0 \Rightarrow \varepsilon_{\check{K},h} \equiv \frac{\partial \check{K}/\check{K}}{\partial h/h} = - \frac{h}{\frac{\partial \check{B}}{\partial \underline{K}} \check{K}} \in \left(- \frac{\underline{K}}{\check{K}}, 0 \right), \end{aligned} \quad (\text{A.6a})$$

$$\begin{aligned} & \frac{\partial \underline{B}}{\partial \underline{K}} \frac{\partial \underline{K}}{\partial p} + \frac{\partial \underline{B}}{\partial \underline{E}} \left[\frac{\partial \underline{E}}{\partial \underline{K}} \frac{\partial \underline{K}}{\partial p} + \frac{\partial \underline{E}}{\partial p} \right] - \frac{\partial \check{B}}{\partial \underline{K}} \frac{\partial \check{K}}{\partial p} - \frac{\partial \check{B}}{\partial \underline{E}} \left[\frac{\partial \check{E}}{\partial \underline{K}} \frac{\partial \check{K}}{\partial p} + \frac{\partial \check{E}}{\partial p} \right] \\ & - p \left[\frac{\partial \underline{E}}{\partial \underline{K}} \frac{\partial \underline{K}}{\partial p} + \frac{\partial \underline{E}}{\partial p} - \frac{\partial \check{E}}{\partial \underline{K}} \frac{\partial \check{K}}{\partial p} - \frac{\partial \check{E}}{\partial p} \right] - [\underline{E} - \check{E}] - h \frac{\partial \underline{K}}{\partial p} = 0 \\ \Leftrightarrow & - \frac{\partial \check{B}}{\partial \underline{K}} \frac{\partial \check{K}}{\partial p} - [\underline{E} - \check{E}] = 0 \Rightarrow \varepsilon_{\check{K},p} \equiv \frac{\partial \check{K}/\check{K}}{\partial p/p} = \frac{p}{\frac{\partial \check{B}}{\partial \underline{K}} \check{K}} \frac{\check{E} - \underline{E}}{\check{K}} = \frac{h}{\frac{\partial \check{B}}{\partial \underline{K}} \check{K}} - \frac{\underline{B} - \check{B}}{\frac{\partial \check{B}}{\partial \underline{K}} \check{K}} \in \left(0, |\varepsilon_{\check{K},h}| \right), \end{aligned} \quad (\text{A.6b})$$

$$\begin{aligned} & \frac{\partial \underline{B}}{\partial \underline{K}} + \frac{\partial \underline{B}}{\partial \underline{E}} \frac{\partial \underline{E}}{\partial \underline{K}} - \left[\frac{\partial \check{B}}{\partial \underline{K}} \frac{\partial \check{K}}{\partial \underline{K}} + \frac{\partial \check{B}}{\partial \underline{E}} \frac{\partial \check{E}}{\partial \underline{K}} \frac{\partial \check{K}}{\partial \underline{K}} \right] - p \left[\frac{\partial \underline{E}}{\partial \underline{K}} - \frac{\partial \check{E}}{\partial \underline{K}} \frac{\partial \check{K}}{\partial \underline{K}} \right] - h = 0 \\ \Leftrightarrow & \frac{\partial \underline{B}}{\partial \underline{K}} - \frac{\partial \check{B}}{\partial \underline{K}} \frac{\partial \check{K}}{\partial \underline{K}} - h = 0 \Rightarrow \varepsilon_{\check{K},\underline{K}} \equiv \frac{\partial \check{K}/\check{K}}{\partial \underline{K}/\underline{K}} = - \frac{h - \frac{\partial \underline{B}}{\partial \underline{K}}}{\frac{\partial \check{B}}{\partial \underline{K}} \check{K}} \in \left(\varepsilon_{\check{K},h}, 0 \right). \end{aligned} \quad (\text{A.6c})$$

Substituting (2.3) into (A.6) yields (2.19). For the more specific energy-services benefit function $B(K_i E_i)$, $\varepsilon_{\check{K},p} = 1 + \varepsilon_{\check{K},h} - \varepsilon_{\check{K},\underline{K}} = -\varepsilon_{\check{K},h} - [\underline{B} - \check{B}]/[p\check{E}]$ implies $\varepsilon_{\check{K},h} < -0.5$.

A.2 Proof of Lemma 1

From (A.6c), we infer $\frac{\partial \check{K}}{\partial \underline{K}} = - \left[h - \frac{\partial \underline{B}}{\partial \underline{K}} \right] / \frac{\partial \check{B}}{\partial \underline{K}}$, which is zero for a weak standard by (A.2b), and negative but greater than minus one for a stricter standard by (A.2c) and $\frac{\partial \check{B}}{\partial \underline{K}} > h$. Next, differentiating (A.6) yields

$$\frac{\partial \varepsilon_{\check{K},h}}{\partial \underline{K}} \Big|_{\underline{K}=K^\circ} = - \frac{h}{\frac{\partial \check{B}}{\partial \underline{K}} \check{K}} < 0, \quad (\text{A.7a})$$

$$\frac{\partial \varepsilon_{\check{K},p}}{\partial \underline{K}} \Big|_{\underline{K}=K^\circ} = \frac{\frac{\partial^2 \underline{B}}{\partial \underline{K} \partial \underline{E}}}{\frac{\partial^2 \underline{B}}{\partial E^2}} \frac{p}{\frac{\partial \check{B}}{\partial \underline{K}} \check{K}} > 0, \quad (\text{A.7b})$$

$$\left. \frac{\partial \varepsilon_{\check{K}, \underline{K}}}{\partial \underline{K}} \right|_{\underline{K}=K^\circ} = \frac{\frac{\partial^2 B}{\partial E^2} \frac{\partial^2 B}{\partial K^2} - \left[\frac{\partial^2 B}{\partial K \partial E} \right]^2}{\frac{\partial^2 B}{\partial E^2}} \frac{\underline{K}}{\frac{\partial \check{B}}{\partial \check{K}} \check{K}} < 0. \quad (\text{A.7c})$$

Finally, by (A.2c) and (A.4), the left-hand side of (2.16) is decreasing in \underline{K} and converges to $-\infty$ for $\underline{K} \rightarrow \infty$, while the right-hand side of (2.16) is greater than or equal to zero and constant. Thus, for each $K_{i,0}$ there is an increase in \underline{K} that changes the sign of (2.16), which proves $\lim_{\underline{K} \rightarrow \infty} \check{K} = 0$. \square

A.3 Derivation of (3.5)

Differentiating (3.3) and rearranging yields

$$\hat{h} = \frac{1 + \frac{\partial \check{K}}{\partial \underline{K}} \frac{\underline{K}}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}}{k' \frac{h}{\check{k}} - \frac{\partial \check{K}}{\partial h} \frac{h}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}} \hat{\underline{K}} + \frac{\frac{\partial \check{K}}{\partial p} \frac{p}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}}{k' \frac{h}{\check{k}} - \frac{\partial \check{K}}{\partial h} \frac{h}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}} \hat{p}, \quad (\text{A.8a})$$

$$\hat{p} = \frac{\frac{\partial \underline{E}}{\partial \underline{K}} \frac{\underline{K}}{\underline{E}} - \frac{\check{E}-\underline{E}}{\underline{E}} \frac{\partial \check{K}}{\partial \underline{K}} \frac{\underline{K}}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}}{\chi(\underline{K}) \left[e' \frac{p}{e} - \frac{\partial \underline{E}}{\partial p} \frac{p}{\underline{E}} \right] + \frac{\check{E}-\underline{E}}{\underline{E}} \frac{\partial \check{K}}{\partial p} \frac{p}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}} \hat{\underline{K}} - \frac{\frac{\check{E}-\underline{E}}{\underline{E}} \frac{\partial \check{K}}{\partial h} \frac{h}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}}{\chi(\underline{K}) \left[e' \frac{p}{e} - \frac{\partial \underline{E}}{\partial p} \frac{p}{\underline{E}} \right] + \frac{\check{E}-\underline{E}}{\underline{E}} \frac{\partial \check{K}}{\partial p} \frac{p}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}} \hat{h}, \quad (\text{A.8b})$$

where

$$\chi(\underline{K}) = 1 + \int_{\check{K}}^{\infty} \frac{g(K_{i,0})}{G(\check{K})} \frac{e' \frac{p}{e} - \frac{\partial E_{i,0}}{\partial p} \frac{p}{E_{i,0}}}{e' \frac{p}{e} - \frac{\partial \underline{E}}{\partial p} \frac{p}{\underline{E}}} \frac{E_{i,0}}{\underline{E}} dK_{i,0} > 1. \quad (\text{A.9})$$

Using the definitions of the elasticities from (2.4), (2.19) and (3.4), and solving for \hat{h} and \hat{p} yields (3.5) and (3.6).

A.4 Proof of Lemma 2

Using (3.5a) and (3.5b) in $d\check{K} = \frac{\partial \check{K}}{\partial \underline{K}} d\underline{K} + \frac{\partial \check{K}}{\partial h} dh + \frac{\partial \check{K}}{\partial p} dp$ yields

$$\frac{d\check{K}}{d\underline{K}} \frac{\underline{K}}{\check{K}} = \varepsilon_{\check{K}, \underline{K}} + \varepsilon_{\check{K}, h} \Omega_{h, \underline{K}} + \varepsilon_{\check{K}, p} \Omega_{p, \underline{K}} = \frac{\chi(\underline{K}) \left[\theta - \varepsilon_{E, p} \right] \left[\eta \varepsilon_{\check{K}, \underline{K}} + \varepsilon_{\check{K}, h} \right] + \eta \varepsilon_{\check{K}, p} \varepsilon_{E, K}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E, p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K}, h} \right] + \check{\gamma} \eta \varepsilon_{\check{K}, p} \frac{\check{E}-\underline{E}}{\underline{E}}}. \quad (\text{A.10})$$

$\frac{d\check{K}}{d\underline{K}} \frac{\underline{K}}{\check{K}}$ is zero for $\underline{K} = K^\circ, \eta, \theta \rightarrow \infty$ or $\check{\gamma} \rightarrow \infty$; otherwise, it is negative.

Using (3.5b) in $d\underline{E} = \frac{\partial \underline{E}}{\partial \underline{K}} d\underline{K} + \frac{\partial \underline{E}}{\partial p} dp$ yields

$$\frac{d\underline{E}}{d\underline{K}} \frac{\underline{K}}{\underline{E}} = \varepsilon_{E, K} + \varepsilon_{E, p} \Omega_{p, \underline{K}} = \varepsilon_{E, K} \frac{\chi(\underline{K}) \theta \left[\eta - \check{\gamma} \varepsilon_{\check{K}, h} \right] + \check{\gamma} \eta \varepsilon_{\check{K}, p} \frac{\check{E}-\underline{E}}{\underline{E}}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E, p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K}, h} \right] + \check{\gamma} \eta \varepsilon_{\check{K}, p} \frac{\check{E}-\underline{E}}{\underline{E}}}$$

$$+ \varepsilon_{E,p} \frac{\eta \left[[1 - \chi(\underline{K})] \varepsilon_{E,K} - \check{\gamma} \varepsilon_{\check{K},\underline{K}} \frac{\check{E}-E}{\underline{E}} \right] - \check{\gamma} \varepsilon_{\check{K},h} \left[[1 - \chi(\underline{K})] \varepsilon_{E,K} + \frac{\check{E}-E}{\underline{E}} \right]}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-E}{\underline{E}}}. \quad (\text{A.11})$$

$\frac{dE}{dK} \frac{K}{E}$ is zero for $\eta, \check{\gamma} = 0$; otherwise, it is negative.

Using (3.4), (3.5a), (3.5b) and (3.5d) in $d \left[\frac{e}{G(\check{K})E} \right] = \frac{de}{G(\check{K})E} - \frac{e}{G(\check{K})E} \frac{E dG(\check{K}) + G(\check{K}) dE}{G(\check{K})E}$ yields

$$\begin{aligned} \frac{d \left[\frac{e}{G(\check{K})E} \right]}{dK} \frac{K}{\frac{e}{G(\check{K})E}} &= \Omega_{e,\underline{K}} - \left[\check{\gamma} \left[\varepsilon_{\check{K},\underline{K}} + \varepsilon_{\check{K},h} \Omega_{h,\underline{K}} + \varepsilon_{\check{K},p} \Omega_{p,\underline{K}} \right] + \varepsilon_{E,K} + \varepsilon_{E,p} \Omega_{p,\underline{K}} \right] \\ &= -\check{\gamma} \frac{\chi(\underline{K}) + \frac{\check{E}-E}{\underline{E}} \chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta \varepsilon_{\check{K},\underline{K}} + \varepsilon_{\check{K},h} \right] + \eta \varepsilon_{\check{K},p} \varepsilon_{E,K}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-E}{\underline{E}}} - \varepsilon_{E,K} \frac{\chi(\underline{K}) - 1}{\chi(\underline{K})}. \end{aligned} \quad (\text{A.12})$$

$\frac{d \left[\frac{e}{G(\check{K})E} \right]}{dK} \frac{K}{\frac{e}{G(\check{K})E}}$ is always positive, such that $\frac{d \left[\frac{G(\check{K})E}{e} \right]}{dK} \frac{K}{\frac{G(\check{K})E}{e}}$ is always negative. \square

A.5 Individual Demand with the Isoelastic Benefit Function

For the more general isoelastic benefit function $B(K_i, E_i) = b \frac{K_i^{1-\kappa} E_i^{1-\epsilon} - 1}{1-\beta}$, (2.2) becomes

$$u_i = Y_i - pE_i - I_i + b \frac{K_i^{1-\kappa} E_i^{1-\epsilon} - 1}{1-\beta} \quad \text{with} \quad I_i = \begin{cases} hK_i & \text{if } K_i > K_{i,0}, \\ 0 & \text{else.} \end{cases} \quad (\text{A.13})$$

Differentiating (A.13) yields the optimal energy demand and the respective elasticities

$$\frac{\partial u_i}{\partial E} = \frac{b}{\beta-1} (\epsilon-1) K_i^{1-\kappa} E_i^{-\epsilon} - p = 0 \Rightarrow E^*(K_i, p) = \left[\frac{b}{\beta-1} \left(\frac{p}{\epsilon-1} \right)^{-1} \right]^{\frac{1}{\epsilon}} K_i^{-\frac{\kappa-1}{\epsilon}}, \quad (\text{A.14a})$$

$$\varepsilon_{E,K} = -\frac{\kappa-1}{\epsilon} < 0, \quad (\text{A.14b})$$

$$\varepsilon_{E,p} = -\frac{1}{\epsilon} \in (-1, 0). \quad (\text{A.14c})$$

Substituting (A.14a) and $I_i = hK_i$ into (A.13) and differentiating yields the optimal unconstrained capital demand and the respective elasticities

$$\begin{aligned} \frac{\partial u_i}{\partial K} &= (\kappa-1) \left[\frac{b}{\beta-1} \left(\frac{p}{\epsilon-1} \right)^{\epsilon-1} \right]^{\frac{1}{\epsilon}} K_i^{-\frac{\kappa+\epsilon-1}{\epsilon}} - h = 0 \\ \Rightarrow K^\circ(h, p) &= \left[\frac{b}{\beta-1} \left(\frac{h}{\kappa-1} \right)^{-\epsilon} \left(\frac{p}{\epsilon-1} \right)^{\epsilon-1} \right]^{\frac{1}{\kappa+\epsilon-1}}, \end{aligned} \quad (\text{A.15a})$$

$$\varepsilon_{K^\circ, h} = -\frac{\epsilon}{\kappa+\epsilon-1} \in (-1, 0), \quad (\text{A.15b})$$

$$\varepsilon_{K^\circ,p} = \frac{\epsilon - 1}{\kappa + \epsilon - 1} \in (0, |\varepsilon_{K^\circ,h}|). \quad (\text{A.15c})$$

Substituting (A.14a) into (2.17) and rearranging yields the cutoff level \check{K} and the respective elasticities

$$\check{K} = \left(1 + \frac{\kappa - 1}{\epsilon} \underline{m}\right)^{-\frac{\epsilon}{\kappa-1}} \underline{K} \text{ with } \underline{m} = \left(\frac{\underline{K}}{\underline{K}^\circ}\right)^{\frac{\kappa+\epsilon-1}{\epsilon}} \geq 1 \text{ and } \frac{\partial \underline{m}}{\partial \underline{K}} = \frac{\kappa + \epsilon - 1}{\epsilon} \frac{\underline{m}}{\underline{K}} > 0, \quad (\text{A.16a})$$

$$\varepsilon_{\check{K},\underline{K}} = -\frac{\underline{m} - 1}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \in \left(-\frac{\epsilon}{\kappa-1}, 0\right] \text{ with } \frac{\partial \varepsilon_{\check{K},\underline{K}}}{\partial \underline{K}} = -\frac{\frac{\kappa+\epsilon-1}{\epsilon}}{\left(\frac{\kappa-1}{\epsilon} \underline{m} + 1\right)^2} \frac{\partial \underline{m}}{\partial \underline{K}} < 0, \quad (\text{A.16b})$$

$$\varepsilon_{\check{K},h} = -\frac{\underline{m}}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \in \left(-\frac{\epsilon}{\kappa-1}, -\frac{\epsilon}{\kappa+\epsilon-1}\right) \text{ with } \frac{\partial \varepsilon_{\check{K},h}}{\partial \underline{K}} = -\frac{1}{\left(\frac{\kappa-1}{\epsilon} \underline{m} + 1\right)^2} \frac{\partial \underline{m}}{\partial \underline{K}} < 0, \quad (\text{A.16c})$$

$$\varepsilon_{\check{K},p} = \frac{\frac{\epsilon-1}{\epsilon} \underline{m}}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \in \left(\frac{\epsilon-1}{\kappa+\epsilon-1}, \frac{\epsilon-1}{\kappa-1}\right) \text{ with } \frac{\partial \varepsilon_{\check{K},p}}{\partial \underline{K}} = \frac{\frac{\epsilon-1}{\epsilon}}{\left(\frac{\kappa-1}{\epsilon} \underline{m} + 1\right)^2} \frac{\partial \underline{m}}{\partial \underline{K}} > 0. \quad (\text{A.16d})$$

A.6 Proof of Lemma 3

Using (A.14a), (A.16a) and (A.14b) in $(\check{E} - \underline{E})/\underline{E}$ yields

$$\frac{\check{E} - \underline{E}}{\underline{E}} = \left(\frac{\underline{K}}{\underline{\check{K}}}\right)^{\frac{\kappa-1}{\epsilon}} - 1 = \frac{\kappa-1}{\epsilon} \underline{m} = -\varepsilon_{E,K} \underline{m}, \quad (\text{A.17})$$

where $\underline{m} > [=]1$ for $\underline{K} > [=]K^\circ$ by (A.16a). Since $\lim_{\underline{K} \rightarrow \infty} \underline{K}^{\frac{\kappa-1}{\epsilon}} = \infty$ and $\check{K}^{-\frac{\kappa-1}{\epsilon}}$ is increasing in \underline{K} by Lemma 2, we have $\lim_{\underline{K} \rightarrow \infty} (\check{E} - \underline{E})/\underline{E} = \infty$. \square

A.7 Proof of Lemma 4

From (A.16), we infer

$$\underline{m} = \frac{\epsilon}{\kappa-1} \left[\left(\frac{\underline{K}}{\underline{\check{K}}}\right)^{\frac{\kappa-1}{\epsilon}} - 1 \right] \text{ with } \frac{d\underline{m}}{d\underline{K}} = \left(\frac{\underline{K}}{\underline{\check{K}}}\right)^{\frac{\kappa-1}{\epsilon}-1} \left(1 - \frac{d\underline{\check{K}}}{d\underline{K}} \frac{\underline{K}}{\underline{\check{K}}}\right) \frac{1}{\underline{\check{K}}} > 0, \quad (\text{A.18a})$$

$$\frac{d\varepsilon_{\check{K},\underline{K}}}{d\underline{K}} = -\frac{\frac{\kappa+\epsilon-1}{\epsilon}}{\left(\frac{\kappa-1}{\epsilon} \underline{m} + 1\right)^2} \frac{d\underline{m}}{d\underline{K}} < 0, \quad (\text{A.18b})$$

$$\frac{d\varepsilon_{\check{K},h}}{d\underline{K}} = -\frac{1}{\left(\frac{\kappa-1}{\epsilon} \underline{m} + 1\right)^2} \frac{d\underline{m}}{d\underline{K}} < 0, \quad (\text{A.18c})$$

$$\frac{d\varepsilon_{\check{K},p}}{d\underline{K}} = \frac{\frac{\epsilon-1}{\epsilon}}{\left(\frac{\kappa-1}{\epsilon} \underline{m} + 1\right)^2} \frac{d\underline{m}}{d\underline{K}} > 0. \quad (\text{A.18d})$$

Thus, we have $\frac{d|\varepsilon_{\check{K},\underline{K}}|}{d\underline{K}} > \frac{d|\varepsilon_{\check{K},h}|}{d\underline{K}} > \frac{d\varepsilon_{\check{K},p}}{d\underline{K}} > 0$. Since $\lim_{\underline{K} \rightarrow \infty} \underline{K}^{\frac{\kappa-1}{\epsilon}} = \infty$ and $\check{K}^{-\frac{\kappa-1}{\epsilon}}$ is increasing in \underline{K} by Lemma 2, we have $\lim_{\underline{K} \rightarrow \infty} \underline{m} = \infty$.

Using $\varepsilon_{E,p}(K_{i,0}) = \varepsilon_{E,p}(\underline{K})$ and (A.14a) in (3.6) yields

$$\chi(\underline{K}) = 1 + \int_{\check{K}}^{\infty} \frac{g(K_{i,0})}{G(\check{K})} \frac{E_{i,0}}{\underline{E}} dK_{i,0} = 1 + \frac{\underline{K}^{\frac{\kappa-1}{\epsilon}}}{G(\check{K})} \int_{\check{K}}^{\infty} g(K_{i,0}) K_{i,0}^{-\frac{\kappa-1}{\epsilon}} dK_{i,0}, \quad (\text{A.19a})$$

$$\frac{d\chi(\underline{K})}{d\underline{K}} = \frac{\underline{K}^{\frac{\kappa-1}{\epsilon}}}{G(\check{K})} \left[\left[\frac{\kappa-1}{\epsilon} \frac{1}{\underline{K}} - \frac{g(\check{K})}{G(\check{K})} \frac{d\check{K}}{d\underline{K}} \right] \int_{\check{K}}^{\infty} g(K_{i,0}) K_{i,0}^{-\frac{\kappa-1}{\epsilon}} dK_{i,0} - g(\check{K}) \check{K}^{-\frac{\kappa-1}{\epsilon}} \frac{d\check{K}}{d\underline{K}} \right] > 0. \quad (\text{A.19b})$$

Since $\lim_{\underline{K} \rightarrow \infty} \underline{K}^{\frac{\kappa-1}{\epsilon}} = \infty$ and $\frac{1}{G(\check{K})} \int_{\check{K}}^{\infty} g(K_{i,0}) K_{i,0}^{-\frac{\kappa-1}{\epsilon}} dK_{i,0}$ is increasing in \underline{K} , we have $\lim_{\underline{K} \rightarrow \infty} \chi(\underline{K}) = \infty$.

Using (3.4), (3.5a), (3.5b), (3.5d) and $\chi(\underline{K}) = \frac{e}{G(\check{K})\underline{E}}$ in $\frac{d[e-G(\check{K})\underline{E}]}{d\underline{K}} = \frac{de}{d\underline{K}} - \frac{G(\check{K})\underline{E}}{\underline{K}} \left[\frac{g(\check{K})\check{K}}{G(\check{K})} \frac{d\check{K}}{d\underline{K}} \frac{\underline{K}}{\underline{E}} + \frac{d\underline{E}}{d\underline{K}} \frac{\underline{K}}{\underline{E}} \right]$ yields

$$\begin{aligned} \frac{d[e-G(\check{K})\underline{E}]}{d\underline{K}} \frac{\underline{K}}{e} &= \Omega_{e,\underline{K}} - \frac{1}{\chi(\underline{K})} \left[\check{\gamma} \left[\varepsilon_{\check{K},\underline{K}} + \varepsilon_{\check{K},h} \Omega_{h,\underline{K}} + \varepsilon_{\check{K},p} \Omega_{p,\underline{K}} \right] + \varepsilon_{E,\underline{K}} + \varepsilon_{E,p} \Omega_{p,\underline{K}} \right] \\ &= -\frac{\check{\gamma}}{\chi(\underline{K})} \frac{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta \varepsilon_{\check{K},\underline{K}} + \varepsilon_{\check{K},h} \right] + \eta \varepsilon_{\check{K},p} \varepsilon_{E,\underline{K}} \frac{\check{E}}{\underline{E}}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}} \underline{E}}. \end{aligned} \quad (\text{A.20})$$

$\frac{d[e-G(\check{K})\underline{E}]}{d\underline{K}} \frac{\underline{K}}{e}$ is zero for $\underline{K} = K^\circ$, $\eta, \theta \rightarrow \infty$ or $\check{\gamma} = 0$; otherwise, it is positive.

Suppose $\check{\gamma} = 0$ or $\underline{K} = K^\circ$. Then, $\Omega_{h,\underline{K}} > 0 \iff \eta \in [0, \infty)$ and $\Omega_{k,\underline{K}} > 0 \iff \eta > 0$ by (3.5a) and (3.5c), respectively. Now suppose $\check{\gamma} > 0$ and $\underline{K} > K^\circ$. Then, $\Omega_{h,\underline{K}} = 0 \iff \eta \rightarrow \infty$, $\Omega_{p,\underline{K}} = 0 \iff \theta \rightarrow \infty$, $\Omega_{k,\underline{K}} = 0 \iff \eta = 0$ and $\Omega_{e,\underline{K}} = 0 \iff \theta = 0$, while $\Omega_{p,\underline{K}} < 0$, $\Omega_{h,\underline{K}} < 0$, $\Omega_{e,\underline{K}} < 0$ and $\Omega_{h,\underline{K}} < 0$ can hold, respectively, by (3.5). Using (3.5) yields

$$\begin{aligned} \underbrace{\eta \varepsilon_{E,\underline{K}}}_{<0 \text{ if } \eta > 0} \Omega_{h,\underline{K}} + \underbrace{\chi(\underline{K}) \left[\varepsilon_{E,p} - \theta \right]}_{<0} \Omega_{p,\underline{K}} &= \underbrace{\varepsilon_{E,\underline{K}} \Omega_{k,\underline{K}}}_{<0} + \underbrace{\chi(\underline{K}) \left[\varepsilon_{E,p} - \theta \right] / \theta \Omega_{e,\underline{K}}}_{<0 \text{ if } \theta < \infty} \\ &= \underbrace{\check{\gamma} \left[\varepsilon_{E,\underline{K}} + \frac{\check{E}-\underline{E}}{\underline{E}} \right]}_{\geq 0} \underbrace{\frac{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta \varepsilon_{\check{K},\underline{K}} + \varepsilon_{\check{K},h} \right] + \eta \varepsilon_{\check{K},p} \varepsilon_{E,\underline{K}}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}}}_{\leq 0} \leq 0. \end{aligned} \quad (\text{A.21})$$

The second line of (A.21) is negative for $\check{\gamma} > 0$ and $\underline{K} > K^\circ$, such that $\Omega_{h,\underline{K}} \leq 0 \implies \Omega_{p,\underline{K}} > 0$ and $\Omega_{p,\underline{K}} \leq 0 \implies \Omega_{h,\underline{K}} > 0$ for $\eta, \theta \in [0, \infty)$, while $\Omega_{k,\underline{K}} \leq 0 \implies \Omega_{e,\underline{K}} > 0$ and $\Omega_{e,\underline{K}} \leq 0 \implies \Omega_{k,\underline{K}} > 0$ for $\eta, \theta > 0$ by the first line of (A.21).

From (3.3) and $\frac{\partial E^*(K_{i,p})}{\partial K} < 0$, the equilibrium is characterized by

$$k(h) = G(\check{K})\underline{K}, \quad (\text{A.22a})$$

$$e(p) = G(\check{K})E(\underline{K}, p) + \int_{\check{K}}^{\infty} g_{i,0}(K_{i,0})E(K_{i,0}, p) dK_{i,0} \leq \int_0^{\infty} g_{i,0}(K_{i,0})E(K_{i,0}, p) dK_{i,0}. \quad (\text{A.22b})$$

The left-hand side of (A.22b) is zero for $p = 0$ and increasing in p , while the right-hand side of

(A.22b) is decreasing in p and converges to zero for $p \rightarrow \infty$, which implies $p \in (0, \infty)$. Thus, $\lim_{\underline{K} \rightarrow \infty} \underline{E} = 0$ by (A.14a). Now suppose $\lim_{\underline{K} \rightarrow \infty} \check{K} > 0$, such that $\lim_{\underline{K} \rightarrow \infty} G(\check{K}) > 0$. Then, the right-hand side of (A.22a) converges to infinity for $\underline{K} \rightarrow \infty$, such that the left-hand side of (A.22a) must converge to infinity for $\underline{K} \rightarrow \infty$, which implies $\lim_{\underline{K} \rightarrow \infty} h = \infty$ for $\eta \in [0, \infty)$. However, $p \in (0, \infty)$ and $\lim_{\underline{K} \rightarrow \infty} h = \infty$ implies $\lim_{\underline{K} \rightarrow \infty} \check{K} = 0$ by (A.15a) and (A.16a), which contradicts $\lim_{\underline{K} \rightarrow \infty} \check{K} > 0$. \square

A.8 Proof of Proposition 3

Using (A.18a), (A.19a) and $G(\check{K}) = g(\check{K})\check{K}/\check{\gamma}$ in $\chi(\underline{K})/\underline{m}$ yields

$$\begin{aligned} \lim_{\underline{K} \rightarrow \infty} \frac{\chi(\underline{K})}{\underline{m}} &= \lim_{\underline{K} \rightarrow \infty} \frac{\kappa-1}{\epsilon} \frac{1}{\left(\frac{\underline{K}}{\check{K}}\right)^{\frac{\kappa-1}{\epsilon}} - 1} \frac{\underline{K}^{\frac{\kappa-1}{\epsilon}}}{G(\check{K})} \int_{\check{K}}^{\infty} g(K_{i,0}) K_{i,0}^{-\frac{\kappa-1}{\epsilon}} dK_{i,0} \\ &= \lim_{\underline{K} \rightarrow \infty} \frac{\kappa-1}{\epsilon} \frac{\check{\gamma}}{\check{K}} \underbrace{\int_{\check{K}}^{\infty} \frac{g(K_{i,0}) K_{i,0}^{-\frac{\kappa-1}{\epsilon}}}{g(\check{K}) \check{K}^{-\frac{\kappa-1}{\epsilon}}} dK_{i,0}}_{\geq 1}. \end{aligned} \quad (\text{A.23})$$

Since $\gamma(0) > 0$ by $\gamma'(K) \leq 0$ and $\lim_{\underline{K} \rightarrow \infty} \check{K} = 0$ by Lemma 4, we have $\lim_{\underline{K} \rightarrow \infty} \chi(\underline{K})/\underline{m} = \infty$.

Using (A.14b), (A.14c), (A.16b), (A.16c), (A.16d) and (A.17) in (3.10a) yields

$$\Omega_{h,\underline{K}} = \frac{\frac{\chi(\underline{K})}{\underline{m}} \left[\theta + \frac{1}{\epsilon} \right] \left[\frac{1}{\check{\gamma}} \frac{\frac{\kappa-1}{\epsilon} \underline{m} + 1}{\underline{m}-1} - 1 \right] + \frac{(\kappa-1)(\epsilon-1)}{\epsilon^2}}{\frac{\chi(\underline{K})}{\underline{m}} \left[\theta + \frac{1}{\epsilon} \right] \left[\frac{\eta}{\check{\gamma}} \frac{\frac{\kappa-1}{\epsilon} \underline{m} + 1}{\underline{m}-1} + \frac{\underline{m}}{\underline{m}-1} \right] + \eta \frac{(\kappa-1)(\epsilon-1)}{\epsilon^2} \frac{\underline{m}}{\underline{m}-1}} \in \left(-\frac{\underline{m}-1}{\underline{m}}, \frac{1}{\eta} \right], \quad (\text{A.24a})$$

$$\lim_{\underline{K} \rightarrow \infty} \Omega_{h,\underline{K}} = \frac{1 - \gamma(0) \frac{\epsilon}{\kappa-1}}{\eta + \gamma(0) \frac{\epsilon}{\kappa-1}} \in \left(-1, \frac{1}{\eta} \right]. \quad (\text{A.24b})$$

Suppose $\gamma(0) \leq \frac{\kappa-1}{\epsilon}$. Then, the second square-bracketed term in the numerator of (A.24a) is positive for $\underline{m} \in [1, \infty) \iff \underline{K} \in [K^\circ, \infty)$, such that $\Omega_{h,\underline{K}}$ is always positive. Suppose $\gamma(0) > \frac{\kappa-1}{\epsilon}$. Then, the second square-bracketed term in the numerator of (A.24a) is positive for $\underline{m} = 1 \iff \underline{K} = K^\circ$, but $\Omega_{h,\underline{K}}$ converges to a negative constant for $\underline{K} \rightarrow \infty$, such that $\Omega_{h,\underline{K}}$ becomes negative at a critical value $\underline{K} = \underline{K}_K$.

Next, we prove that this critical value is unique. Differentiating (3.10a) and using (A.10) yields

$$\begin{aligned} \frac{d\Omega_{h,\underline{K}}}{d\underline{K}} &= \frac{-\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \check{\gamma} \varepsilon_{\check{K},p}^{\varepsilon_{E,K}} \left\{ \check{\gamma} \underline{m} \varepsilon_{\check{K},\underline{K}} + \eta \left[1 + \check{\gamma} \underline{m} \varepsilon_{\check{K},\underline{K}} \right] \right\}}{\underbrace{\underline{K} \left\{ \chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p}^{\frac{\check{E}-\underline{E}}{\underline{E}}} \right\}^2}_{\leq 0 \iff \Omega_{h,\underline{K}} \leq 0}} \left[\frac{d\chi(\underline{K})/\chi(\underline{K})}{d\underline{K}/\underline{K}} - \frac{d\underline{m}/\underline{m}}{d\underline{K}/\underline{K}} \right] \\ &\quad + \underbrace{\left\{ \frac{-\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \varepsilon_{\check{K},\underline{K}} [1 - \varepsilon_{E,K}] \frac{d\check{K}}{d\underline{K}} \frac{\underline{K}}{\check{K}}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p}^{\frac{\check{E}-\underline{E}}{\underline{E}}}} \right\}}_{\leq 0} \end{aligned}$$

$$\begin{aligned}
& + \frac{-\left\{ \chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \varepsilon_{\check{K},\underline{K}} - \eta \varepsilon_{\check{K},p} \left[\varepsilon_{E,K} + \frac{\check{E}-\underline{E}}{\underline{E}} \right] \right\} \Omega_{h,\underline{K}}}{\underbrace{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}}_{\leq 0 \iff \Omega_{h,\underline{K}} \leq 0}} \underbrace{\frac{\check{\gamma}}{[\underline{m}-1]^2} \frac{d\underline{m}}{d\underline{K}}}_{\geq 0} \\
& + \frac{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \frac{d\check{K}}{d\underline{K}}}{\underbrace{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}}_{\leq 0}} \underbrace{\check{\gamma}' \frac{d\check{K}}{d\underline{K}}}_{\geq 0}, \tag{A.25}
\end{aligned}$$

where

$$\begin{aligned}
& \frac{d\chi(\underline{K})/\chi(\underline{K})}{d\underline{K}/\underline{K}} - \frac{d\underline{m}/\underline{m}}{d\underline{K}/\underline{K}} = \underbrace{\frac{\eta}{\check{\gamma} \underline{m} \varepsilon_{\check{K},\underline{K}}} \Omega_{h,\underline{K}}}_{\geq 0 \iff \Omega_{h,\underline{K}} \leq 0} + \underbrace{\frac{-1}{\check{\gamma} \underline{m} \varepsilon_{\check{K},\underline{K}}}}_{> 0} \\
& \cdot \frac{\left[\theta - \varepsilon_{E,p} \right] \left\{ \chi(\underline{K}) \left[1 + \check{\gamma} \varepsilon_{\check{K},\underline{K}} \right] - \check{\gamma} \underline{m} \varepsilon_{\check{K},\underline{K}} \varepsilon_{E,K} \right\} \left\{ \check{\gamma} \underline{m} \varepsilon_{\check{K},\underline{K}} + \eta \left[1 + \check{\gamma} \underline{m} \varepsilon_{\check{K},\underline{K}} \right] \right\}}{\underbrace{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}}_{> 0 \iff \Omega_{h,\underline{K}} \leq 0}} \tag{A.26}
\end{aligned}$$

by (A.12) and (A.18a). Thus, $\Omega_{h,\underline{K}}(\underline{K}) < 0$ implies $\frac{d\Omega_{h,\underline{K}}(\underline{K})}{d\underline{K}} \leq 0$ and, thus, $\Omega_{h,\underline{K}}(\underline{K}') < 0$ for all $\underline{K}' > \underline{K}$.

Using (A.14b), (A.14c), (A.16b), (A.16c), (A.16d) and (A.17) in (3.10b) yields

$$\Omega_{p,\underline{K}} = \frac{\frac{\eta}{\underline{m}} \frac{\kappa-1}{\epsilon} \left[\check{\gamma} \frac{\underline{m}(\underline{m}-1)}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \frac{1+\eta}{\eta} - 1 \right]}{\frac{\chi(\underline{K})}{\underline{m}} \left[\theta + \frac{1}{\epsilon} \right] \left[\eta + \check{\gamma} \frac{\underline{m}}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \right] + \check{\gamma} \eta \frac{\frac{\epsilon-1}{\epsilon} \underline{m}}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \frac{\kappa-1}{\epsilon}} \geq \frac{\varepsilon_{E,K}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right]}, \tag{A.27a}$$

$$\lim_{\underline{K} \rightarrow \infty} \Omega_{p,\underline{K}} = 0. \tag{A.27b}$$

Suppose $\eta'(h) < 0$ and $\gamma(0) \leq \frac{\kappa-1}{\epsilon}$, such that $\frac{d\eta(h)}{dh} = \eta'(h) \Omega_{h,\underline{K}} \frac{h}{\underline{K}} < 0$, or $\eta'(h) = 0$. Then, the square-bracketed term in the numerator of (A.27a) is negative for $\underline{m} = 1 \iff \underline{K} = K^\circ$, but is increasing in \underline{K} and converges to infinity for $\underline{K} \rightarrow \infty$, such that $\Omega_{p,\underline{K}}$ becomes positive at a unique critical value $\underline{K} = \underline{K}_e$. $\Omega_{e,\underline{K}} \leq 0 \implies \Omega_{k,\underline{K}} > 0$ from Lemma 4 then implies $\underline{K}_e < \underline{K}_K$.

From (3.3) and $\lim_{\underline{K} \rightarrow \infty} \underline{E} = 0$, the equilibrium on the energy market is characterized by

$$e(p^\circ) = G(\check{K}) E(K^\circ, p^\circ) + \int_{\check{K}}^{\infty} g_{i,0}(K_{i,0}) E(K_{i,0}, p^\circ) dK_{i,0} \tag{A.28}$$

for $\underline{K} \leq K^\circ$ and by

$$e(p) = \int_0^{\infty} g_{i,0}(K_{i,0}) E(K_{i,0}, p) dK_{i,0} \tag{A.29}$$

for $\underline{K} \rightarrow \infty$. Suppose $p \leq p^\circ$. Then, the left-hand side of (A.29) would not exceed the left-hand side of (A.28), whereas the right-hand side of (A.29) would exceed the right-hand side

of (A.28), which is a contradiction. Thus, $p > p^\circ$. □

A.9 Derivation of (3.11)

By (A.27a), the critical value $\underline{K} = \underline{K}_e$ is implicitly defined by

$$\underline{m} = \frac{1}{2} \left(1 + \frac{\eta}{\check{\gamma}(1+\eta)} \frac{\kappa-1}{\epsilon} \right) + \sqrt{\left[\frac{1}{2} \left(1 + \frac{\eta}{\check{\gamma}(1+\eta)} \frac{\kappa-1}{\epsilon} \right) \right]^2 + \frac{\eta}{\check{\gamma}(1+\eta)}}. \quad (\text{A.30})$$

Using (A.14b) and (A.16a) in (A.30) and rearranging yields (3.11). The right-hand side of (3.11) increases with $\frac{\eta}{\check{\gamma}(1+\eta)}$. Furthermore,

$$\frac{\partial \left(\frac{\underline{K}_e}{\check{K}} \right)}{\partial (|\varepsilon_{E,K}|)} = \frac{\frac{\underline{K}_e}{\check{K}}}{(|\varepsilon_{E,K}|)^2} \Gamma, \quad (\text{A.31})$$

where

$$\Gamma = |\varepsilon_{E,K}| \frac{1 + \frac{2\eta|\varepsilon_{E,K}|}{\check{\gamma}(1+\eta)} - \left(\frac{\underline{K}_e}{\check{K}} \right)^{-|\varepsilon_{E,K}|}}{\sqrt{\left(1 + \frac{\eta|\varepsilon_{E,K}|}{\check{\gamma}(1+\eta)} \right)^2 + \frac{4\eta}{\check{\gamma}(1+\eta)}}} - \ln \left(\left(\frac{\underline{K}_e}{\check{K}} \right)^{|\varepsilon_{E,K}|} \right), \quad (\text{A.32a})$$

$$\frac{\partial \Gamma}{\partial \eta} = - \frac{\frac{\eta[|\varepsilon_{E,K}|]^2}{\check{\gamma}^2(1+\eta)^3} \left[1 + \frac{\eta|\varepsilon_{E,K}|}{\check{\gamma}(1+\eta)} \right]}{\left[\left(1 + \frac{\eta|\varepsilon_{E,K}|}{\check{\gamma}(1+\eta)} \right)^2 + \frac{4\eta}{\check{\gamma}(1+\eta)} \right]^{\frac{3}{2}}} < 0, \quad (\text{A.32b})$$

$$\Gamma|_{\eta=0} = \frac{|\varepsilon_{E,K}|}{1 + |\varepsilon_{E,K}|} - \ln(1 + |\varepsilon_{E,K}|) < 0 \text{ since } \ln(x) \in \left(\frac{x-1}{x}, x-1 \right), \quad (\text{A.32c})$$

such that the right-hand side of (3.11) decreases with $|\varepsilon_{E,K}|$. Using $\frac{\eta}{\check{\gamma}(1+\eta)} \geq 0$ and $|\varepsilon_{E,K}| \leq 1$ in (3.11) yields $\underline{K}_e / \check{K} \geq 2$.

A.10 Derivation of (4.2)

For the general energy-services benefit function $B(K_i, E_i)$, we define the *potential energy savings* as the energy savings that would result if the prices of capital and energy did not change ($\eta, \theta \rightarrow \infty$), all investing households continued to invest ($\varepsilon_{\check{K}, \underline{K}} = 0$), and all investing households consumed energy such that their benefit of energy consumption did not change ($dB(\underline{K}, \underline{E}) = 0$). Then, the *potential elasticity of energy savings* is given by $\frac{G(\check{K})\underline{E}}{e} \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}$, where $\frac{G(\check{K})\underline{E}}{e}$ is the share of energy consumed by the investing households, and $\frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}$ is the potential elasticity of energy savings of an investing household. (Note that $dB(\underline{K}, \underline{E}) = 0 \Leftrightarrow \frac{\partial \underline{E}}{\partial \underline{K}} \frac{\underline{K}}{\underline{E}} = -\frac{\frac{\partial B}{\partial \underline{K}} \underline{K}}{\frac{\partial B}{\partial \underline{E}} \underline{E}} = -\frac{\kappa-1}{\epsilon-1} = \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}$.) Using the *actual elasticity of energy savings* $= \Omega_{e,\underline{K}}$ and the *potential*

elasticity of energy savings $= \frac{G(\check{K})\underline{E}}{e} \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}} = \frac{1}{\chi(\underline{K})} \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}$ in (4.1) yields

$$R = \underbrace{-\varepsilon_{E,p}}_{DE>0} + \underbrace{\frac{1+\varepsilon_{E,p}}{\varepsilon_{E,K}} \check{\gamma} \varepsilon_{\check{K},\underline{K}} \frac{\check{E}-\underline{E}}{\underline{E}}}_{IE\geq 0} + \underbrace{CPE(\eta, \check{\gamma}) + EPE(\theta, \check{\gamma}) + RPE(\eta, \theta, \check{\gamma})}_{PE\geq 0}, \quad (\text{A.33})$$

where

$$\begin{aligned} PE &\equiv CPE(\eta, \check{\gamma}) + EPE(\theta, \check{\gamma}) + RPE(\eta, \theta, \check{\gamma}) \\ &= \left\{ \frac{\left\{ \chi(\underline{K}) \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] \varepsilon_{E,p} - \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}} \right\} \left[-\varepsilon_{E,K} + \check{\gamma} \varepsilon_{\check{K},\underline{K}} \frac{\check{E}-\underline{E}}{\underline{E}} \right]}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}} \right. \\ &\quad \left. + \frac{\chi(\underline{K}) \check{\gamma} \theta \varepsilon_{\check{K},h} \frac{\check{E}-\underline{E}}{\underline{E}} \left[1 + \check{\gamma} \varepsilon_{\check{K},\underline{K}} \right]}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}} \right\} \frac{1+\varepsilon_{E,p}}{\varepsilon_{E,K}}, \end{aligned} \quad (\text{A.34})$$

and where

$$CPE(\eta, \check{\gamma}) \equiv \frac{\check{\gamma} \varepsilon_{\check{K},h} \frac{\check{E}-\underline{E}}{\underline{E}} \left[1 + \check{\gamma} \varepsilon_{\check{K},\underline{K}} \right]}{\eta - \check{\gamma} \varepsilon_{\check{K},h}} \frac{1+\varepsilon_{E,p}}{\varepsilon_{E,K}}, \quad (\text{A.35a})$$

$$EPE(\theta, \check{\gamma}) \equiv \frac{\left[\chi(\underline{K}) \varepsilon_{E,p} - \check{\gamma} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}} \right] \left[-\varepsilon_{E,K} + \check{\gamma} \varepsilon_{\check{K},\underline{K}} \frac{\check{E}-\underline{E}}{\underline{E}} \right]}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] + \check{\gamma} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}} \frac{1+\varepsilon_{E,p}}{\varepsilon_{E,K}}, \quad (\text{A.35b})$$

$$RPE(\eta, \theta, \check{\gamma}) \equiv \frac{\Omega_{h,\underline{K}} \left[\chi(\underline{K}) \varepsilon_{E,p} \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] - \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}} \right] - \check{\gamma} \varepsilon_{\check{K},p} \left[-\varepsilon_{E,K} + \check{\gamma} \varepsilon_{\check{K},\underline{K}} \frac{\check{E}-\underline{E}}{\underline{E}} \right]}{\left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] \left\{ \chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] + \check{\gamma} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}} \right\} / \left[\check{\gamma} \varepsilon_{\check{K},h} \frac{\check{E}-\underline{E}}{\underline{E}} \frac{1+\varepsilon_{E,p}}{\varepsilon_{E,K}} \right]}. \quad (\text{A.35c})$$

For $\underline{K} = K^\circ$ or $\underline{K} > K^\circ \wedge \Omega_{p,\underline{K}} \leq 0$, we have $-\varepsilon_{E,K} + \check{\gamma} \varepsilon_{\check{K},\underline{K}} \frac{\check{E}-\underline{E}}{\underline{E}}, 1 + \check{\gamma} \varepsilon_{\check{K},\underline{K}} > 0 \wedge \Omega_{h,\underline{K}} \geq 0$, such that $PE, CPE, EPE \geq 0 \wedge RPE \leq 0$. Thereby, $PE = 0$ if and only if $\eta \wedge \theta \rightarrow \infty$, $CPE = 0$ if and only if $\eta \rightarrow \infty \vee \check{\gamma} = 0$, $EPE = 0$ if and only if $\theta \rightarrow \infty$, and $RPE = 0$ if and only if $\eta \vee \theta \rightarrow \infty \vee \check{\gamma} = 0$. For the general energy-services benefit function $B(K_i, E_i)$, the IE is strong when the potential elasticity of energy savings of an investing household $= \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}$ is small. For the more specific energy-services benefit function $B(K_i E_i)$, substituting $\frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}} = -1$ from (2.5) into (A.33) yields (4.2).

A.11 Proof of Lemma 5

Differentiating (A.33) yields

$$\frac{\partial R}{\partial \eta} = \frac{-\frac{\partial \Omega_{e,\underline{K}}}{\partial \eta}}{\frac{1}{\chi(\underline{K})} \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}} = \frac{\Omega_{h,\underline{K}}}{\frac{1}{\chi(\underline{K})} \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}} \frac{-\check{\gamma} \theta \varepsilon_{\check{K},h} \frac{\check{E}-\underline{E}}{\underline{E}}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}}, \quad (\text{A.36a})$$

$$\frac{\partial R}{\partial \theta} = \frac{-\frac{\partial \Omega_{e,K}}{\partial \theta}}{\frac{1}{\chi(\underline{K})} \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}} = \frac{-\Omega_{p,K}}{\frac{1}{\chi(\underline{K})} \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}} \frac{-\chi(\underline{K})\varepsilon_{E,p} \left[\eta - \check{\gamma}\varepsilon_{\check{K},h} \right] + \check{\gamma}\eta\varepsilon_{\check{K},p} \frac{\check{E}-E}{E}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma}\varepsilon_{\check{K},h} \right] + \check{\gamma}\eta\varepsilon_{\check{K},p} \frac{\check{E}-E}{E}}, \quad (\text{A.36b})$$

$$\begin{aligned} \frac{\partial^2 R}{\partial \eta \partial \theta} &= \frac{-\frac{\partial^2 \Omega_{e,K}}{\partial \eta \partial \theta}}{\frac{1}{\chi(\underline{K})} \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}} = \frac{-\check{\gamma}\varepsilon_{\check{K},h} \frac{\check{E}-E}{E}}{\frac{1}{\chi(\underline{K})} \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}} \\ &\quad \cdot \frac{\Omega_{h,K} \left\{ -\chi(\underline{K})\varepsilon_{E,p} \left[\eta - \check{\gamma}\varepsilon_{\check{K},h} \right] + \check{\gamma}\eta\varepsilon_{\check{K},p} \frac{\check{E}-E}{E} \right\} - \Omega_{p,K}\chi(\underline{K})\check{\gamma}\theta\varepsilon_{\check{K},p}}{\left\{ \chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma}\varepsilon_{\check{K},h} \right] + \check{\gamma}\eta\varepsilon_{\check{K},p} \frac{\check{E}-E}{E} \right\}^2}, \end{aligned} \quad (\text{A.36c})$$

$$\frac{\partial R}{\partial \check{\gamma}} = \frac{-\frac{\partial \Omega_{e,K}}{\partial \check{\gamma}}}{\frac{1}{\chi(\underline{K})} \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}} = \frac{\theta\eta \frac{\check{E}-E}{E}}{\frac{1}{\chi(\underline{K})} \frac{\varepsilon_{E,K}}{1+\varepsilon_{E,p}}} \frac{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta\varepsilon_{\check{K},K} + \varepsilon_{\check{K},h} \right] + \eta\varepsilon_{\check{K},p}\varepsilon_{E,K}}{\left\{ \chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma}\varepsilon_{\check{K},h} \right] + \check{\gamma}\eta\varepsilon_{\check{K},p} \frac{\check{E}-E}{E} \right\}^2}. \quad (\text{A.36d})$$

For $\Omega_{e,K} \leq 0$, we have $\Omega_{p,K} \leq 0 \wedge \Omega_{h,K} \geq 0$ by Lemma 4, such that $\frac{\partial R}{\partial \eta}, \frac{\partial R}{\partial \theta}, \frac{\partial^2 R}{\partial \eta \partial \theta} \leq 0 \wedge \frac{\partial R}{\partial \check{\gamma}} \geq 0$. Thereby, $\frac{\partial R}{\partial \eta} = 0$ if and only if $\eta \rightarrow \infty \vee \theta = 0 \vee \check{\gamma} = 0$, $\frac{\partial R}{\partial \theta} = 0$ if and only if $\theta \rightarrow \infty$, $\frac{\partial^2 R}{\partial \eta \partial \theta} = 0$ if and only if $\eta \rightarrow \infty \vee \theta \rightarrow \infty \vee \check{\gamma} = 0$, and $\frac{\partial R}{\partial \check{\gamma}} = 0$ if and only if $\eta = 0 \vee \theta = 0 \vee \check{\gamma} \rightarrow \infty$. \square

A.12 Proof of Proposition 4

Differentiating (A.33) yields

$$\frac{dR}{d\underline{K}} = -\theta \frac{1 + \varepsilon_{E,p}}{\varepsilon_{E,K}} \frac{d \left[\chi(\underline{K}) \Omega_{p,K} \right]}{d\underline{K}}, \quad (\text{A.37})$$

where

$$\begin{aligned} \frac{d \left[\chi(\underline{K}) \Omega_{p,K} \right]}{d\underline{K}} &= \frac{\check{\gamma}\eta\varepsilon_{\check{K},p} \frac{\check{E}-E}{E} \Omega_{p,K}}{\underbrace{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma}\varepsilon_{\check{K},h} \right] + \check{\gamma}\eta\varepsilon_{\check{K},p} \frac{\check{E}-E}{E}}_{\geq 0 \iff \Omega_{p,K} \geq 0}} \underbrace{\frac{d\chi(\underline{K})}{d\underline{K}}}_{>0} \\ &\quad + \left\{ \frac{\chi(\underline{K})\eta^2 \left[\theta - \varepsilon_{E,p} \right] \varepsilon_{\check{K},h}\varepsilon_{E,K}}{\underbrace{\left\{ \chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma}\varepsilon_{\check{K},h} \right] + \check{\gamma}\eta\varepsilon_{\check{K},p} \frac{\check{E}-E}{E} \right\}^2}_{>0}} \right. \\ &\quad + \frac{\check{\gamma}\varepsilon_{\check{K},h} \frac{\check{E}-E}{E} \left[\eta + 1 \right] \left\{ \chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \varepsilon_{\check{K},h} + \eta\varepsilon_{\check{K},p}\varepsilon_{E,K} \right\}}{\underbrace{\left\{ \chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma}\varepsilon_{\check{K},h} \right] + \check{\gamma}\eta\varepsilon_{\check{K},p} \frac{\check{E}-E}{E} \right\}^2}_{>0}} \\ &\quad \left. + \frac{-\eta \left[\varepsilon_{\check{K},h}\varepsilon_{E,K} + \frac{\check{E}-E}{E} \right] \frac{d\check{K}}{d\underline{K}}}{\underbrace{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma}\varepsilon_{\check{K},h} \right] + \check{\gamma}\eta\varepsilon_{\check{K},p} \frac{\check{E}-E}{E}}_{>0}} \right\} \underbrace{\chi(\underline{K}) \frac{\check{\gamma}}{m} \frac{dm}{d\underline{K}}}_{>0} \end{aligned}$$

$$\begin{aligned}
& + \underbrace{\frac{-\eta \frac{\check{E}-E}{E} \frac{d\check{K}}{d\check{K}} \frac{K}{\check{K}}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-E}{E}}_{>0} \underbrace{\chi(\underline{K}) \check{\gamma}' \frac{d\check{K}}{d\check{K}}}_{\geq 0} \\
& + \underbrace{\frac{\check{\gamma} \varepsilon_{\check{K},h} \frac{\check{E}-E}{E} \Omega_{h,\underline{K}}^2 \frac{h}{\underline{K}} \eta' - \chi(\underline{K}) \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] \Omega_{p,\underline{K}}^2 \frac{p}{\underline{K}} \theta'}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-E}{E}}_{\geq 0 \iff \eta', \theta' \leq 0} \quad (A.38a) \\
& = \left\{ \frac{\eta \varepsilon_{\check{K},p} \left\{ \left[\theta - \varepsilon_{E,p} - \varepsilon_{\check{K},p} / \varepsilon_{\check{K},h} \right] \Omega_{p,\underline{K}}^2 - \left[\eta + 1 \right] \Omega_{h,\underline{K}} \Omega_{p,\underline{K}} \right\}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-E}{E}} \right. \\
& \quad \left. + \frac{\left[1 - \frac{d\check{K}}{d\check{K}} \frac{K}{\check{K}} \right] \left\{ \eta \left[1 - \frac{d\check{K}}{d\check{K}} \frac{K}{\check{K}} / \underline{m} \right] + 1 \right\}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-E}{E}} \right\} \underbrace{\chi(\underline{K}) \frac{\check{\gamma}}{\underline{K}} \frac{\check{E}-E}{E}}_{>0} \\
& \quad + \underbrace{\frac{-\eta \frac{\check{E}-E}{E} \frac{d\check{K}}{d\check{K}} \frac{K}{\check{K}}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-E}{E}}_{>0} \underbrace{\chi(\underline{K}) \check{\gamma}' \frac{d\check{K}}{d\check{K}}}_{\geq 0} \\
& \quad + \underbrace{\frac{\check{\gamma} \varepsilon_{\check{K},h} \frac{\check{E}-E}{E} \Omega_{h,\underline{K}}^2 \frac{h}{\underline{K}} \eta' - \chi(\underline{K}) \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] \Omega_{p,\underline{K}}^2 \frac{p}{\underline{K}} \theta'}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-E}{E}}_{\geq 0 \iff \eta', \theta' \leq 0}. \quad (A.38b)
\end{aligned}$$

Suppose $\eta', \theta' \leq 0$. Then, $\frac{dR}{d\check{K}} = 0$ if $\theta = 0$ or $\eta, \check{\gamma} = 0$ or $\check{\gamma}, \check{\gamma}', \theta' = 0$; otherwise, $\frac{dR}{d\check{K}} > 0$. \square

A.13 Calibration

From the distribution of vehicle ages, the production shares of passenger cars and the past CAFE standards of Table 1, the distribution of the current U.S. passenger car fuel economy is illustrated in Figure 4. We approximated this distribution by minimizing the sum of squared distances (SSD) to the data points from the logistic distribution $G(K) = \frac{1}{1+e^{-x(K-\bar{K})}}$ with $x = 0.4737$, $K_{\min} = 29.01$ and $\check{\gamma} = 8.480$ (SSD = 0.191) illustrated in the left panel of Figure 4, from the exponential distribution $G(K) = 1 - e^{-x(K-K_{\min})}$ with $x = 0.07527$, $K_{\min} = 18.00$ and $\check{\gamma} \rightarrow \infty$ (SSD = 0.775), from the logarithmic distribution $G(K) = \left[\frac{\ln(1+K-K_{\min})}{\ln(1+K_{\max}-K_{\min})} \right]^x$ with $x = 3.539$, $K_{\min} = 18$, $K_{\max} = 39$ and $\check{\gamma} \rightarrow \infty$ (SSD = 0.351), and from the isoelastic distribution $G(K) = \left(\frac{K}{K_{\max}} \right)^{\check{\gamma}}$ with $K_{\max} = 39.00$ and $\check{\gamma} = 2.957$ (SSD = 0.548). However, the distribution for $K \in [18, 26.5]$ can best be approximated by the uniform distribution $G(K) = \frac{K-K_{\min}}{K_{\max}-K_{\min}}$ with $K_{\min} = 16.81$, $K_{\max} = 251.6$ and $\check{\gamma} = 15.21$ illustrated in the right panel of Figure 4.

Finally, we use the actual distribution of the current U.S. passenger car fuel economy to

Table 1: Vehicle ages, production shares of passenger cars and past CAFE standards

Year	Vehicles	PC/(PC+LT) Production	PC Share	PC CAFE
1978	752	100.0%	0.555%	18.0
1979	833	90.2%	0.555%	19.0
1980	655	83.3%	0.403%	20.0
1981	647	82.4%	0.394%	22.0
1982	905	79.9%	0.534%	24.0
1983	1091	77.5%	0.624%	26.0
1984	1882	75.6%	1.050%	27.5
1985	602	74.1%	0.329%	26.0
1986	653	71.4%	0.344%	26.0
1987	687	71.9%	0.365%	26.0
1988	701	69.9%	0.362%	26.5
1989	866	69.2%	0.443%	27.5
1990	986	69.8%	0.508%	27.5
1991	1002	67.8%	0.501%	27.5
1992	1223	66.6%	0.601%	27.5
1993	1574	64.0%	0.744%	27.5
1994	2018	59.6%	0.887%	27.5
1995	2731	62.0%	1.251%	27.5
1996	2795	60.0%	1.238%	27.5
1997	3873	57.6%	1.648%	27.5
1998	4615	55.1%	1.878%	27.5
1999	5875	55.1%	2.387%	27.5
2000	7440	55.1%	3.024%	27.5
2001	8242	53.9%	3.277%	27.5
2002	9126	51.5%	3.470%	27.5
2003	10359	50.2%	3.840%	27.5
2004	11578	48.0%	4.100%	27.5
2005	12782	50.5%	4.766%	27.5
2006	13183	52.9%	5.150%	27.5
2007	13636	52.9%	5.325%	27.5
2008	13628	52.7%	5.298%	27.5
2009	10250	60.5%	4.577%	27.5
2010	12067	54.5%	4.857%	27.5
2011	12291	47.8%	4.336%	30.2
2012	14967	55.0%	6.073%	33.0
2013	16705	54.1%	6.674%	33.5
2014	17175	49.2%	6.243%	34.2
2015	17823	47.2%	6.208%	35.5
2016	13683	43.8%	4.425%	36.9
2017	2496	41.0%	0.756%	39.0

Note: PC: passenger cars, LT: light trucks (95% of household vehicles are passenger cars or light trucks). 6765 vehicles are from 1984 or earlier and we distribute these vehicles between 1978 and 1984 according to their shares in FHWA (2001, VEHYEAR). $PC\ Share = [Vehicles_t \cdot PC_t / (PC_t + LT_t)] / \sum_{t=1978}^{t=2017} [Vehicles_t \cdot PC_t / (PC_t + LT_t)]$.

Source: Vehicles: FHWA (2017, VEHYEAR), PC/(PC+LT) Production: NHTSA (2014) and BTS (2021, Table 1-20), PC CAFE: NHTSA (2014) and BTS (2021, Table 4-23).

derive the share of energy consumed by the investing households. From (A.14a) and $-\frac{\kappa-1}{\epsilon} = -1 + |\varepsilon_{E,p}|$, we have $E_t = (K_t/K)^{-1+|\varepsilon_{E,p}|}\underline{E}$. Thus, the share of energy consumed by the investing households is given by

$$\frac{G(\check{K})\underline{E}}{e} = \frac{PC_{2017}\underline{E}}{\sum_{t=1978}^{2017} PC_t E_t} = \frac{PC_{2017}K^{-1+|\varepsilon_{E,p}|}}{\sum_{t=1978}^{2017} PC_t K_t^{-1+|\varepsilon_{E,p}|}}, \quad (\text{A.39})$$

where

$$\frac{\partial \left[\frac{G(\check{K})\underline{E}}{e} \right]}{\partial |\varepsilon_{E,p}|} = \frac{G(\check{K})\underline{E}}{e} \frac{\sum_{t=1978}^{2017} PC_t K_t^{-1+|\varepsilon_{E,p}|} \ln \left(\frac{K}{K_t} \right)}{\sum_{t=1978}^{2017} PC_t K_t^{-1+|\varepsilon_{E,p}|}} > 0. \quad (\text{A.40})$$

Using PC_t and K_t from Table 1, we have $[G(\check{K})\underline{E}/e]|_{|\varepsilon_{E,p}|=0} = 0.56\%$, $[G(\check{K})\underline{E}/e]|_{|\varepsilon_{E,p}|=0.25} = 0.61\%$ and $[G(\check{K})\underline{E}/e]|_{|\varepsilon_{E,p}|=1} = 0.76\%$.

A.14 Proof of Proposition 5

Using (A.6) as well as (3.5a) in (4.4) yields:

$$\begin{aligned} & \left[\frac{\partial \underline{B}}{\partial \underline{K}} - h \right] - \frac{d\underline{h}}{d\underline{K}} \underline{K} = \left[\varepsilon_{\check{K},\underline{K}} + \Omega_{h,\underline{K}} \varepsilon_{\check{K},h} \right] \frac{h}{-\varepsilon_{\check{K},h}} \\ &= \frac{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\varepsilon_{\check{K},h} + \eta \varepsilon_{\check{K},\underline{K}} \right] + \check{\gamma} \varepsilon_{\check{K},p} \left\{ \varepsilon_{\check{K},h} \left[\varepsilon_{E,K} + \frac{\check{E}-\underline{E}}{\underline{E}} \right] + \eta \varepsilon_{\check{K},\underline{K}} \frac{\check{E}-\underline{E}}{\underline{E}} \right\}}{\chi(\underline{K}) \left[\theta - \varepsilon_{E,p} \right] \left[\eta - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \eta \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}} \frac{h}{-\varepsilon_{\check{K},h}} < 0. \end{aligned} \quad (\text{A.41})$$

Using (A.6) as well as (3.5a), (3.5b), (A.14b), (A.14c), (A.16b), (A.16c), (A.16d) and (A.17) in (4.4) yields:

$$\begin{aligned} \frac{d\underline{u}}{d\underline{K}} &= \left[-\Omega_{p,\underline{K}} \varepsilon_{\check{K},p} \frac{\underline{E}}{\check{E}-\underline{E}} + \varepsilon_{\check{K},\underline{K}} + \Omega_{h,\underline{K}} \varepsilon_{\check{K},h} \right] \frac{h}{-\varepsilon_{\check{K},h}} \\ &= - \frac{\chi(\underline{K}) \left[\theta + \frac{1}{\epsilon} \right] \left[\underline{m} + \eta(\underline{m}-1) \right] - \eta \frac{\epsilon-1}{\epsilon} + \check{\gamma}(\eta+1) \frac{\epsilon-1}{\epsilon} \underline{m}(\underline{m}-1)}{\chi(\underline{K}) \left[\theta + \frac{1}{\epsilon} \right] \left[\eta + \check{\gamma} \frac{\underline{m}}{\epsilon \underline{m}+1} \right] + \check{\gamma} \eta \frac{\epsilon-1}{\epsilon} \frac{\underline{m}}{\epsilon \underline{m}+1}} \frac{h}{\underline{m}}. \end{aligned} \quad (\text{A.42})$$

The numerator of (A.42) is increasing in \underline{K} and converges to infinity, such that (A.42) is either always negative or becomes negative at a unique critical value $\underline{K} = \underline{K}_u < \underline{K}_e$. (A.42) is always negative if and only if $\chi(K^\circ) \left[\theta + \frac{1}{\epsilon} \right] - \eta \frac{\epsilon-1}{\epsilon} \geq 0 \iff \eta \leq \chi(K^\circ)^{\frac{\theta+|\varepsilon_{E,p}|}{1-|\varepsilon_{E,p}|}}$, and it is positive for $\underline{K} = K^\circ$ if and only if $\eta > \chi(K^\circ)^{\frac{\theta+|\varepsilon_{E,p}|}{1-|\varepsilon_{E,p}|}}$.

Using (A.6) as well as $e = \chi(\underline{K})G(\check{K})\underline{E}$, (3.5a), (3.5b), (A.14b), (A.14c), (A.16b), (A.16c), (A.16d) and (A.17) in (4.3) and (4.4) yields:

$$\int_0^{\check{K}} g(K_{i,0}) \underline{u} dK_{i,0} + \int_{\check{K}}^\infty g(K_{i,0}) u_{i,0} dK_{i,0} = \left[-\chi(\underline{K}) \Omega_{p,\underline{K}} \varepsilon_{\check{K},p} \frac{\underline{E}}{\check{E}-\underline{E}} + \varepsilon_{\check{K},\underline{K}} + \Omega_{h,\underline{K}} \varepsilon_{\check{K},h} \right] \frac{hG(\check{K})}{-\varepsilon_{\check{K},h}}$$

$$= - \frac{\chi(\underline{K}) \left\{ \left[\theta + \frac{1}{\epsilon} \right] \left[\underline{m} + \eta(\underline{m} - 1) \right] - \eta \frac{\epsilon-1}{\epsilon} \right\} + \frac{\frac{\kappa-1}{\epsilon} \underline{m} + \chi(\underline{K})}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \check{\gamma}(\eta + 1) \frac{\epsilon-1}{\epsilon} \underline{m}(\underline{m} - 1) hG(\check{K})}{\chi(\underline{K}) \left[\theta + \frac{1}{\epsilon} \right] \left[\eta + \check{\gamma} \frac{\underline{m}}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \right] + \check{\gamma} \eta \frac{\frac{\epsilon-1}{\epsilon} \underline{m}}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \frac{\kappa-1}{\epsilon} \underline{m}} \underline{m}. \quad (\text{A.43})$$

(A.43) is always negative if and only if $\theta + \frac{1}{\epsilon} - \eta \frac{\epsilon-1}{\epsilon} \geq 0 \iff \eta \leq \frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|}$, and it is positive for $\underline{K} = K^\circ$ if and only if $\eta > \frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|}$.

Using (A.6) as well as $k = G(\check{K})\underline{K}$, $e = \chi(\underline{K})G(\check{K})\underline{E}$, (3.5a), (3.5b), (A.14b), (A.14c), (A.16b), (A.16c), (A.16d) and (A.17) in (4.5a) and (4.5b) yields:

$$\begin{aligned} \frac{d\pi_k}{d\underline{K}} + \frac{d\pi_e}{d\underline{K}} &= \Omega_{h,\underline{K}} \frac{hk}{\underline{K}} + \Omega_{p,\underline{K}} \frac{pe}{\underline{K}} = \left[\chi(\underline{K}) \Omega_{p,\underline{K}} \varepsilon_{\check{K},p} \frac{\underline{E}}{\check{E} - \underline{E}} - \Omega_{h,\underline{K}} \varepsilon_{\check{K},h} \right] \frac{hG(\check{K})}{-\varepsilon_{\check{K},h}} \\ &= \frac{\chi(\underline{K}) \left[1 + \check{\gamma} \varepsilon_{\check{K},\underline{K}} \right] \left[\theta + \frac{1}{\epsilon} - \eta \frac{\epsilon-1}{\epsilon} \right] + \left[\chi(\underline{K}) \eta / \underline{m} + \check{\gamma} \frac{\frac{\kappa-1}{\epsilon} \underline{m} + \chi(\underline{K})}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \right] \frac{\epsilon-1}{\epsilon} (m-1)}{\chi(\underline{K}) \left[\theta + \frac{1}{\epsilon} \right] \left[\eta + \check{\gamma} \frac{\underline{m}}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \right] + \check{\gamma} \eta \frac{\frac{\epsilon-1}{\epsilon} \underline{m}}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \frac{\kappa-1}{\epsilon} \underline{m}} hG(\check{K}) \quad (\text{A.44a}) \\ &= \frac{\chi(\underline{K}) \left\{ \theta + \frac{1}{\epsilon} - \eta \frac{\epsilon-1}{\epsilon} / \underline{m} + \check{\gamma} \varepsilon_{\check{K},\underline{K}} \left[\theta + \frac{1}{\epsilon} - (\eta + 1) \frac{\epsilon-1}{\epsilon} \right] \right\} - \check{\gamma} \varepsilon_{\check{K},\underline{K}} \frac{(\epsilon-1)(\kappa-1)}{\epsilon^2} \underline{m}}{\chi(\underline{K}) \left[\theta + \frac{1}{\epsilon} \right] \left[\eta + \check{\gamma} \frac{\underline{m}}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \right] + \check{\gamma} \eta \frac{\frac{\epsilon-1}{\epsilon} \underline{m}}{\frac{\kappa-1}{\epsilon} \underline{m} + 1} \frac{\kappa-1}{\epsilon} \underline{m}} hG(\check{K}). \quad (\text{A.44b}) \end{aligned}$$

(A.44a) [(A.44b)] is always positive if $\theta + \frac{1}{\epsilon} - \eta \frac{\epsilon-1}{\epsilon} \geq 0 \iff \eta \leq \frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|}$ and $\gamma(0) \leq 1/|\varepsilon_{\check{K},\underline{K}}(0)| = |\varepsilon_{E,K}| \left[\theta + \frac{1}{\epsilon} - (\eta + 1) \frac{\epsilon-1}{\epsilon} \leq 0 \iff \eta \geq \frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|} - 1 \right]$, and it is negative [positive] for $\underline{K} = K^\circ$ if and only if $\eta > [\leq] \frac{\theta + |\varepsilon_{E,p}|}{1 - |\varepsilon_{E,p}|}$.

Finally, using (A.43) and (A.44) in (4.8) for $\lambda_k = \lambda_e = 1$ yields

$$\begin{aligned} \frac{dw}{d\underline{K}} &= \left\{ (1 - \lambda) \left[\chi(\underline{K}) \Omega_{p,\underline{K}} \varepsilon_{\check{K},p} \frac{\underline{E}}{\check{E} - \underline{E}} - \Omega_{h,\underline{K}} \varepsilon_{\check{K},h} \right] + \lambda \varepsilon_{\check{K},\underline{K}} \right\} \frac{hG(\check{K})}{-\varepsilon_{\check{K},h}} = 0 \\ \Leftrightarrow \quad \lambda &= 1 + \frac{\varepsilon_{\check{K},\underline{K}}}{\chi(\underline{K}) \Omega_{p,\underline{K}} \varepsilon_{\check{K},p} \frac{\underline{E}}{\check{E} - \underline{E}} - \Omega_{h,\underline{K}} \varepsilon_{\check{K},h}}. \quad (\text{A.45}) \end{aligned}$$

Using (3.5a), (3.5b), (A.14b), (A.14c), (A.16b), (A.16c), (A.16d), (A.17) and (A.18a) in (A.45) for $\epsilon = \kappa = 4$, $\theta = \eta = 1$, $\check{K} = 18$, $\check{\gamma} = 15.21$ and $\chi(\underline{K}) = 1/0.61\%$ yields λ as a function of \underline{K} , which is shown in Figure 7. \square

A.15 Energy Supply Tax and Capital Supply Subsidy

With an energy supply tax τ and a capital supply subsidy σ , the equilibrium is characterized by

$$k(h + \sigma) = G(\check{K})\underline{K}, \quad (\text{A.46a})$$

$$e(p - \tau) = G(\check{K})\underline{E} + \int_{\check{K}}^{\infty} g(K_{i,0})E_{i,0} dK_{i,0}. \quad (\text{A.46b})$$

Differentiating (A.46) and rearranging yields

$$\hat{h} = -\frac{k' \frac{\sigma}{k}}{k' \frac{h}{k} - \frac{\partial \check{K}}{\partial h} \frac{h}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}} \hat{\sigma} + \frac{1 + \frac{\partial \check{K}}{\partial \check{K}} \frac{K}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}}{k' \frac{h}{k} - \frac{\partial \check{K}}{\partial h} \frac{h}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}} \hat{K} + \frac{\frac{\partial \check{K}}{\partial p} \frac{p}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}}{k' \frac{h}{k} - \frac{\partial \check{K}}{\partial h} \frac{h}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}} \hat{p}, \quad (\text{A.47a})$$

$$\begin{aligned} \hat{p} = & \frac{e' \frac{\tau}{G(\check{K})\underline{E}}}{\chi(\underline{K}) \left[e' \frac{p}{e} - \frac{\partial \underline{E}}{\partial p} \frac{p}{\underline{E}} \right] + \frac{\check{E}-\underline{E}}{\underline{E}} \frac{\partial \check{K}}{\partial p} \frac{p}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}} \hat{\tau} + \frac{\frac{\partial \underline{E}}{\partial \check{K}} \frac{K}{\underline{E}} - \frac{\check{E}-\underline{E}}{\underline{E}} \frac{\partial \check{K}}{\partial \check{K}} \frac{K}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}}{\chi(\underline{K}) \left[e' \frac{p}{e} - \frac{\partial \underline{E}}{\partial p} \frac{p}{\underline{E}} \right] + \frac{\check{E}-\underline{E}}{\underline{E}} \frac{\partial \check{K}}{\partial p} \frac{p}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}} \hat{K} \\ & - \frac{\frac{\check{E}-\underline{E}}{\underline{E}} \frac{\partial \check{K}}{\partial h} \frac{h}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}}{\chi(\underline{K}) \left[e' \frac{p}{e} - \frac{\partial \underline{E}}{\partial p} \frac{p}{\underline{E}} \right] + \frac{\check{E}-\underline{E}}{\underline{E}} \frac{\partial \check{K}}{\partial p} \frac{p}{\check{K}} \frac{g(\check{K})\check{K}}{G(\check{K})}} \hat{h}, \end{aligned} \quad (\text{A.47b})$$

where $\chi(\underline{K})$ is defined by (A.9). Using the definitions of the elasticities from (2.4), (2.19), (3.4) and

$$\bar{\eta}(h + \sigma) \equiv \frac{\partial k(h + \sigma)/k(h + \sigma)}{\partial h/h}, \quad \bar{\theta}(p - \tau) \equiv \frac{\partial e(p - \tau)/e(p - \tau)}{\partial p/p}, \quad (\text{A.48})$$

and solving for \hat{h} and \hat{p} yields

$$\begin{aligned} \hat{h} = & -\frac{\bar{\eta} \frac{\sigma}{h} \left[\chi(\underline{K}) [\bar{\theta} - \varepsilon_{E,p}] + \check{\gamma} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}} \right]}{\chi(\underline{K}) [\bar{\theta} - \varepsilon_{E,p}] [\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h}] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}} \hat{\sigma} \\ & + \frac{\bar{\theta} \frac{\tau}{p} \frac{e}{G(\check{K})\underline{E}} \check{\gamma} \varepsilon_{\check{K},p}}{\chi(\underline{K}) [\bar{\theta} - \varepsilon_{E,p}] [\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h}] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}} \hat{\tau} \\ & + \frac{\chi(\underline{K}) [\bar{\theta} - \varepsilon_{E,p}] \left[1 + \check{\gamma} \varepsilon_{\check{K},\underline{K}} \right] + \check{\gamma} \varepsilon_{\check{K},p} \left[\varepsilon_{E,K} + \frac{\check{E}-\underline{E}}{\underline{E}} \right]}{\chi(\underline{K}) [\bar{\theta} - \varepsilon_{E,p}] [\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h}] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}} \hat{K}, \end{aligned} \quad (\text{A.49a})$$

$$\begin{aligned} \hat{p} = & \frac{\bar{\eta} \frac{\sigma}{h} \check{\gamma} \varepsilon_{\check{K},h} \frac{\check{E}-\underline{E}}{\underline{E}}}{\chi(\underline{K}) [\bar{\theta} - \varepsilon_{E,p}] [\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h}] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}} \hat{\sigma} \\ & + \frac{\bar{\theta} \frac{\tau}{p} \frac{e}{G(\check{K})\underline{E}} [\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h}]}{\chi(\underline{K}) [\bar{\theta} - \varepsilon_{E,p}] [\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h}] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}} \hat{\tau} \\ & + \frac{\bar{\eta} \left[\varepsilon_{E,K} - \check{\gamma} \varepsilon_{\check{K},\underline{K}} \frac{\check{E}-\underline{E}}{\underline{E}} \right] - \check{\gamma} \varepsilon_{\check{K},h} \left[\varepsilon_{E,K} + \frac{\check{E}-\underline{E}}{\underline{E}} \right]}{\chi(\underline{K}) [\bar{\theta} - \varepsilon_{E,p}] [\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h}] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}} \hat{K}, \end{aligned} \quad (\text{A.49b})$$

such that $\hat{h}/\hat{\sigma} < 0$ (if $\bar{\eta} > 0$), $\hat{h}/\hat{\tau} > 0$ (if $\bar{\theta} > 0, \bar{\eta} < \infty$), $\hat{p}/\hat{\sigma} < 0$ (if $\bar{\theta} < \infty, \bar{\eta} > 0$), and $\hat{p}/\hat{\tau} > 0$ (if $\bar{\theta} > 0$). Furthermore, $\hat{k}/\hat{\tau} = \bar{\eta} \hat{h}/\hat{\tau} > 0$ (if $\bar{\theta}, \bar{\eta} > 0$), and $\hat{e}/\hat{\sigma} = \bar{\theta} \hat{p}/\hat{\sigma} < 0$ (if $\bar{\theta}, \bar{\eta} > 0$).

Finally, using (A.49) in $\frac{dk}{d\sigma} = k' \left[\frac{dh}{d\sigma} + 1 \right] = \bar{\eta} \left[\frac{dh}{d\sigma} + 1 \right] \frac{k}{h}$ and $\frac{de}{d\tau} = e' \left[\frac{dp}{d\tau} - 1 \right] = \bar{\theta} \left[\frac{dp}{d\tau} - 1 \right] \frac{e}{p}$ yields

$$\frac{dk}{d\sigma} = -\bar{\eta} \frac{\chi(K) \left[\bar{\theta} - \varepsilon_{E,p} \right] \check{\gamma} \varepsilon_{\check{K},h}}{\chi(K) \left[\bar{\theta} - \varepsilon_{E,p} \right] \left[\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-E}{\bar{E}}} \frac{k}{h}, \quad (\text{A.50a})$$

$$\frac{de}{d\tau} = -\bar{\theta} \frac{-\bar{\chi}(K) \varepsilon_{E,p} \left[\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-E}{\bar{E}}}{\chi(K) \left[\bar{\theta} - \varepsilon_{E,p} \right] \left[\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-E}{\bar{E}}} \frac{e}{p}, \quad (\text{A.50b})$$

where

$$\bar{\chi}(K) = 1 + \int_{\check{K}}^{\infty} \frac{g(K_{i,0})}{G(\check{K})} \frac{\frac{\partial E_{i,0}}{\partial p} \frac{p}{E_{i,0}} \frac{E_{i,0}}{E}}{\frac{\partial \bar{E}}{\partial p} \frac{p}{\bar{E}}} dK_{i,0} > 1, \quad (\text{A.51})$$

such that $\frac{dk}{d\sigma} > 0$ (if $\bar{\eta} > 0$), and $\frac{de}{d\tau} < 0$ (if $\bar{\theta} > 0$).

Now consider a higher energy supply tax or a stricter standard to reduce aggregate energy consumption by one percent for $\sigma = 0$. Suppose the energy firms receive α of the tax revenues and each of the N households receives $(1 - \alpha)/N$ of the tax revenues. From (2.2) and (2.3), gross consumption utility of the non-investing households develops by:

$$\begin{aligned} -\frac{du_{i,0}}{de} e \Big|_{\tau} &= -\frac{du_{i,0}}{d\tau} \frac{e}{\frac{de}{d\tau}} = \frac{\frac{dp}{d\tau} \frac{\tau}{p}}{\frac{de}{d\tau} \frac{\tau}{e}} p E_{i,0} - \frac{1 - \alpha}{N} \frac{1 + \frac{de}{d\tau} \frac{\tau}{e}}{\frac{de}{d\tau} \frac{\tau}{e}} \tau e < 0 \text{ if } \alpha = 1 \\ &= \frac{1}{\theta} p E_{i,0} - \frac{1 - \alpha}{N} \tau e + \frac{\tau}{\frac{de}{d\tau} \frac{\tau}{e}} [E_{i,0} - (1 - \alpha)e/N], \end{aligned} \quad (\text{A.52a})$$

$$-\frac{du_{i,0}}{de} e \Big|_{\underline{K}} = -\frac{du_{i,0}}{d\underline{K}} \frac{e}{\frac{de}{d\underline{K}}} = \frac{1}{\theta} p E_{i,0} - \frac{1 - \alpha}{N} \tau e > 0 \text{ if } \alpha = 1. \quad (\text{A.52b})$$

Thus, non-investing households prefer a higher energy supply tax over a stricter standard if and only if $E_{i,0} < (1 - \alpha)e/N$, and they prefer a stricter standard over a higher energy supply tax if $\alpha = 1$. Furthermore, from (2.2), (2.3) and (2.13), consumption utility of the investing households develops by:

$$\begin{aligned} -\frac{du}{de} e \Big|_{\tau} &= -\frac{du}{d\tau} \frac{e}{\frac{de}{d\tau}} = \frac{\frac{dp}{d\tau} \frac{\tau}{p}}{\frac{de}{d\tau} \frac{\tau}{e}} p \bar{E} - \frac{1 - \alpha}{N} \frac{1 + \frac{de}{d\tau} \frac{\tau}{e}}{\frac{de}{d\tau} \frac{\tau}{e}} \tau e + \frac{\frac{dh}{d\tau} \frac{\tau}{h}}{\frac{de}{d\tau} \frac{\tau}{e}} h \bar{K} < 0 \text{ if } \alpha = 1 \\ &= \frac{1}{\theta} p \bar{E} - \frac{1 - \alpha}{N} \tau e + \frac{\frac{dh}{d\tau} \frac{\tau}{h}}{\frac{de}{d\tau} \frac{\tau}{e}} h \bar{K} + \frac{\tau}{\frac{de}{d\tau} \frac{\tau}{e}} [\bar{E} - (1 - \alpha)e/N], \end{aligned} \quad (\text{A.53a})$$

$$-\frac{du}{de} e \Big|_{\underline{K}} = -\frac{du}{d\underline{K}} \frac{e}{\frac{de}{d\underline{K}}} = \frac{1}{\theta} p \bar{E} - \frac{1 - \alpha}{N} \tau e + \frac{\frac{dh}{d\underline{K}} \frac{\underline{K}}{h}}{\frac{de}{d\underline{K}} \frac{\underline{K}}{e}} h \bar{K} + \frac{h}{\frac{de}{d\underline{K}} \frac{\underline{K}}{e}} \frac{\partial B}{\partial \underline{K}} \underline{K}, \quad (\text{A.53b})$$

where

$$\begin{aligned}
\frac{\frac{dh}{d\tau} \frac{\tau}{h}}{\frac{de}{d\tau} \frac{\tau}{e}} - \frac{\frac{dh}{dK} \frac{K}{h}}{\frac{de}{dK} \frac{K}{e}} &= - \frac{\frac{e}{G(\underline{K})\underline{E}} \check{\gamma} \varepsilon_{\check{K},p}}{-\bar{\chi}(\underline{K}) \varepsilon_{E,p} [\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h}] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}} \\
&+ \frac{1}{\bar{\theta}} \frac{\chi(\underline{K}) [\bar{\theta} - \varepsilon_{E,p}] [1 + \check{\gamma} \varepsilon_{\check{K},K}] + \check{\gamma} \varepsilon_{\check{K},p} [\varepsilon_{E,K} + \frac{\check{E}-\underline{E}}{\underline{E}}]}{-\bar{\eta} [\varepsilon_{E,K} - \check{\gamma} \varepsilon_{\check{K},K} \frac{\check{E}-\underline{E}}{\underline{E}}] + \check{\gamma} \varepsilon_{\check{K},h} [\varepsilon_{E,K} + \frac{\check{E}-\underline{E}}{\underline{E}}]} \\
&= \frac{1}{\bar{\theta}} \frac{\chi(\underline{K}) [\bar{\theta} - \varepsilon_{E,p}] [\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h}] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}}{-\bar{\chi}(\underline{K}) \varepsilon_{E,p} [\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h}] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}} \\
&\cdot \frac{-\bar{\chi}(\underline{K}) \varepsilon_{E,p} [1 + \check{\gamma} \varepsilon_{\check{K},K}] + \check{\gamma} \varepsilon_{\check{K},p} [\varepsilon_{E,K} + \frac{\check{E}-\underline{E}}{\underline{E}}]}{-\bar{\eta} [\varepsilon_{E,K} - \check{\gamma} \varepsilon_{\check{K},K} \frac{\check{E}-\underline{E}}{\underline{E}}] + \check{\gamma} \varepsilon_{\check{K},h} [\varepsilon_{E,K} + \frac{\check{E}-\underline{E}}{\underline{E}}]} > 0. \tag{A.54}
\end{aligned}$$

Thus, investing households prefer a higher energy supply tax over a stricter standard if $\underline{E} \leq (1 - \alpha)e/N$, and they prefer a stricter standard over a higher energy supply tax if $\alpha = 1$ and $\underline{K} \leq \underline{K}_u$. Finally, from (A.52) and (A.53), total consumption utility of the households develops by:

$$\begin{aligned}
-\frac{du}{de} e \Big|_{\tau} &= -\frac{du}{d\tau} \frac{e}{\frac{de}{d\tau}} = \frac{\frac{dp}{d\tau} \frac{\tau}{p}}{\frac{de}{d\tau} \frac{\tau}{e}} pe - (1 - \alpha) \frac{1 + \frac{de}{d\tau} \frac{\tau}{e}}{\frac{de}{d\tau} \frac{\tau}{e}} \tau e + \frac{\frac{dh}{d\tau} \frac{\tau}{h}}{\frac{de}{d\tau} \frac{\tau}{e}} hk < 0 \text{ if } \alpha = 1 \\
&= \frac{1}{\bar{\theta}} pe - (1 - \alpha) \tau e + \frac{\frac{dh}{d\tau} \frac{\tau}{h}}{\frac{de}{d\tau} \frac{\tau}{e}} hk + \frac{\tau}{\frac{de}{d\tau} \frac{\tau}{e}} \alpha e, \tag{A.55a}
\end{aligned}$$

$$-\frac{du}{de} e \Big|_{\underline{K}} = -\frac{du}{d\underline{K}} \frac{e}{\frac{de}{d\underline{K}}} = \frac{1}{\bar{\theta}} pe - (1 - \alpha) \tau e + \frac{\frac{dh}{d\underline{K}} \frac{K}{h}}{\frac{de}{d\underline{K}} \frac{K}{e}} hk + \frac{h - \frac{\partial B}{\partial \underline{K}}}{\frac{de}{d\underline{K}} \frac{K}{e}} k. \tag{A.55b}$$

Thus, the households prefer on average a higher energy supply tax over a stricter standard if $\alpha = 0$, and they prefer a stricter standard over a higher energy supply tax if $\alpha = 1$ and $\underline{K} \leq \underline{K}_u$. From (3.2), the capital firms' profit develops by:

$$-\frac{d\pi_k}{de} e \Big|_{\tau} = -\frac{d\pi_k}{d\tau} \frac{e}{\frac{de}{d\tau}} = -\frac{\frac{dh}{d\tau} \frac{\tau}{h}}{\frac{de}{d\tau} \frac{\tau}{e}} hk > 0, \tag{A.56a}$$

$$-\frac{d\pi_k}{de} e \Big|_{\underline{K}} = -\frac{d\pi_k}{d\underline{K}} \frac{e}{\frac{de}{d\underline{K}}} = -\frac{\frac{dh}{d\underline{K}} \frac{K}{h}}{\frac{de}{d\underline{K}} \frac{K}{e}} hk > 0. \tag{A.56b}$$

Thus, capital firms prefer a stricter standard over a higher energy supply tax from (A.54). Furthermore, from (3.2), the energy firms' profit develops by:

$$-\frac{d\pi_e}{de} e \Big|_{\tau} = -\frac{d\pi_e}{d\tau} \frac{e}{\frac{de}{d\tau}} = -\frac{1}{\bar{\theta}} pe - \alpha \frac{1 + \frac{de}{d\tau} \frac{\tau}{e}}{\frac{de}{d\tau} \frac{\tau}{e}} \tau e, \tag{A.57a}$$

$$-\frac{d\pi_e}{de}\Big|_{\underline{K}} = -\frac{d\pi_e}{d\underline{K}} \frac{e}{\frac{de}{d\underline{K}}} = -\frac{1}{\theta}pe - \alpha\tau e < 0. \quad (\text{A.57b})$$

Thus, energy firms prefer a higher energy supply tax over a stricter standard if and only if $\alpha > 0$. Finally, total welfare develops by

$$-\frac{dw}{de}\Big|_{\tau} = (\lambda - \lambda_k) \frac{\frac{dh}{d\tau} \frac{\tau}{h}}{\frac{de}{d\tau} \frac{\tau}{e}} hk + (\lambda - \lambda_e) \left[\frac{1}{\theta}pe + \alpha \frac{1 + \frac{de}{d\tau} \frac{\tau}{e}}{\frac{de}{d\tau} \frac{\tau}{e}} \tau e \right] - \lambda\tau e, \quad (\text{A.58a})$$

$$-\frac{dw}{de}\Big|_{\underline{K}} = (\lambda - \lambda_k) \frac{\frac{dh}{d\underline{K}} \frac{K}{h}}{\frac{de}{d\underline{K}} \frac{K}{e}} hk + (\lambda - \lambda_e) \left[\frac{1}{\theta}pe + \alpha\tau e \right] - \lambda\tau e + \lambda \frac{h - \frac{\partial B}{\partial \underline{K}} k}{\frac{de}{d\underline{K}} \frac{K}{e}}. \quad (\text{A.58b})$$

Thus, society prefers a higher energy supply tax over a stricter standard if $\lambda_e \geq \lambda \geq \lambda_k$.

Next consider a higher capital supply subsidy or a stricter standard to increase aggregate investment by one percent for $\tau = 0$. Suppose the capital firms pay α of the subsidy costs and each of the N households pays $(1 - \alpha)/N$ of the subsidy costs. From (2.2) and (2.3), gross consumption utility of the non-investing households develops by:

$$\frac{du_{i,0}}{dk}\Big|_{\sigma} = \frac{du_{i,0}}{d\sigma} \frac{k}{\frac{dk}{d\sigma}} = -\frac{\frac{dp}{d\sigma} \frac{\sigma}{p}}{\frac{dk}{d\sigma} \frac{\sigma}{k}} pE_{i,0} - \frac{1 - \alpha}{N} \frac{1 + \frac{dk}{d\sigma} \frac{\sigma}{k}}{\frac{dk}{d\sigma} \frac{\sigma}{k}} \sigma k > 0 \text{ if } \alpha = 1, \quad (\text{A.59a})$$

$$\frac{du_{i,0}}{dk}\Big|_{\underline{K}} = \frac{du_{i,0}}{d\underline{K}} \frac{k}{\frac{d\underline{K}}{d\underline{K}}} = -\frac{\frac{dp}{d\underline{K}} \frac{K}{p}}{\frac{d\underline{K}}{d\underline{K}} \frac{K}{k}} pE_{i,0} - \frac{1 - \alpha}{N} \sigma k > 0 \text{ if } \alpha = 1, \quad (\text{A.59b})$$

where

$$\begin{aligned} \frac{\frac{dp}{d\underline{K}} \frac{K}{p}}{\frac{d\underline{K}}{d\underline{K}} \frac{K}{k}} - \frac{\frac{dp}{d\sigma} \frac{\sigma}{p}}{\frac{dk}{d\sigma} \frac{\sigma}{k}} &= \frac{1}{\bar{\eta}} \frac{\bar{\eta} \left[\varepsilon_{E,K} - \check{\gamma} \varepsilon_{\check{K},\check{K}} \frac{\check{E}-\underline{E}}{\underline{E}} \right] - \check{\gamma} \varepsilon_{\check{K},h} \left[\varepsilon_{E,K} + \frac{\check{E}-\underline{E}}{\underline{E}} \right]}{\chi(\underline{K}) \left[\bar{\theta} - \varepsilon_{E,p} \right] \left[1 + \check{\gamma} \varepsilon_{\check{K},\check{K}} \right] + \check{\gamma} \varepsilon_{\check{K},p} \left[\varepsilon_{E,K} + \frac{\check{E}-\underline{E}}{\underline{E}} \right]} + \frac{\frac{\check{E}-\underline{E}}{\underline{E}}}{\chi(\underline{K}) \left[\bar{\theta} - \varepsilon_{E,p} \right]} \\ &= \frac{1}{\bar{\eta}} \frac{\chi(\underline{K}) \left[\bar{\theta} - \varepsilon_{E,p} \right] \left[\bar{\eta} - \check{\gamma} \varepsilon_{\check{K},h} \right] + \check{\gamma} \bar{\eta} \varepsilon_{\check{K},p} \frac{\check{E}-\underline{E}}{\underline{E}}}{\chi(\underline{K}) \left[\bar{\theta} - \varepsilon_{E,p} \right] \left[1 + \check{\gamma} \varepsilon_{\check{K},\check{K}} \right] + \check{\gamma} \varepsilon_{\check{K},p} \left[\varepsilon_{E,K} + \frac{\check{E}-\underline{E}}{\underline{E}} \right]} \frac{\varepsilon_{E,K} + \frac{\check{E}-\underline{E}}{\underline{E}}}{\chi(\underline{K}) \left[\bar{\theta} - \varepsilon_{E,p} \right]} \geq 0. \end{aligned} \quad (\text{A.60})$$

Thus, non-investing households prefer a higher capital supply subsidy over a stricter standard if $\alpha = 1$ and $\underline{K} > K^\circ$, and they prefer a stricter standard over a higher capital tax if $\alpha < 1$ and $\underline{K} = K^\circ$. Furthermore, from (2.2), (2.3) and (2.13), consumption utility of the investing households develops by:

$$\begin{aligned} \frac{du}{dk}\Big|_{\sigma} &= \frac{du}{d\sigma} \frac{k}{\frac{dk}{d\sigma}} = -\frac{\frac{dp}{d\sigma} \frac{\sigma}{p}}{\frac{dk}{d\sigma} \frac{\sigma}{k}} p\underline{E} - \frac{1 - \alpha}{N} \frac{1 + \frac{dk}{d\sigma} \frac{\sigma}{k}}{\frac{dk}{d\sigma} \frac{\sigma}{k}} \sigma k - \frac{\frac{dh}{d\sigma} \frac{\sigma}{h}}{\frac{dk}{d\sigma} \frac{\sigma}{k}} h\underline{K} > 0 \text{ if } \alpha = 1 \\ &= -\frac{\frac{dp}{d\underline{K}} \frac{K}{p}}{\frac{d\underline{K}}{d\underline{K}} \frac{K}{k}} p\underline{E} - \frac{1 - \alpha}{N} \sigma k - \frac{1}{\bar{\eta}} h\underline{K} + \frac{\sigma}{\frac{dk}{d\sigma} \frac{\sigma}{k}} \left[\underline{K} - (1 - \alpha)k/N \right], \end{aligned} \quad (\text{A.61a})$$

$$\left. \frac{du}{dk} k \right|_{\underline{K}} = \frac{du}{d\underline{K}} \frac{k}{\frac{dk}{d\underline{K}}} = -\frac{\frac{dp}{d\underline{K}} \frac{\underline{K}}{p}}{\frac{dk}{d\underline{K}} \frac{\underline{K}}{k}} pE - \frac{1-\alpha}{N} \sigma k - \frac{1}{\eta} h \underline{K} - \frac{h - \frac{\partial B}{\partial \underline{K}}}{\frac{dk}{d\underline{K}} \frac{\underline{K}}{k}} \underline{K}. \quad (\text{A.61b})$$

Thus, investing households prefer a higher capital supply subsidy over a stricter standard. Finally, from (A.59) and (A.53), total consumption utility of the households develops by:

$$\begin{aligned} \left. \frac{du}{dk} k \right|_{\sigma} &= \frac{du}{d\sigma} \frac{k}{\frac{dk}{d\sigma}} = -\frac{\frac{dp}{d\sigma} \frac{\sigma}{p}}{\frac{dk}{d\sigma} \frac{\sigma}{k}} pE - (1-\alpha) \frac{1 + \frac{dk}{d\sigma} \frac{\sigma}{k}}{\frac{dk}{d\sigma} \frac{\sigma}{k}} \sigma k - \frac{\frac{dh}{d\sigma} \frac{\sigma}{h}}{\frac{dk}{d\sigma} \frac{\sigma}{k}} h k > 0 \text{ if } \alpha = 1 \\ &= -\frac{\frac{dp}{d\underline{K}} \frac{\underline{K}}{p}}{\frac{dk}{d\underline{K}} \frac{\underline{K}}{k}} pE - (1-\alpha) \sigma k - \frac{1}{\eta} h k + \frac{\sigma}{\frac{dk}{d\sigma} \frac{\sigma}{k}} \alpha k, \end{aligned} \quad (\text{A.62a})$$

$$\left. \frac{du}{dk} k \right|_{\underline{K}} = \frac{du}{d\underline{K}} \frac{k}{\frac{dk}{d\underline{K}}} = -\frac{\frac{dp}{d\underline{K}} \frac{\underline{K}}{p}}{\frac{dk}{d\underline{K}} \frac{\underline{K}}{k}} pE - (1-\alpha) \sigma k - \frac{1}{\eta} h k - \frac{h - \frac{\partial B}{\partial \underline{K}}}{\frac{dk}{d\underline{K}} \frac{\underline{K}}{k}} k. \quad (\text{A.62b})$$

Thus, the households prefer on average a higher capital supply subsidy over a stricter standard if $\alpha > 0$ or $\underline{K} > K^\circ$. From (3.2), the capital firms' profit develops by:

$$\left. \frac{d\pi_k}{dk} k \right|_{\sigma} = \frac{d\pi_k}{d\sigma} \frac{k}{\frac{dk}{d\sigma}} = \frac{1}{\eta} h k - \alpha \frac{1 + \frac{dk}{d\sigma} \frac{\sigma}{k}}{\frac{dk}{d\sigma} \frac{\sigma}{k}} \sigma k > 0 \text{ if } \alpha = 0, \quad (\text{A.63a})$$

$$\left. \frac{d\pi_k}{dk} k \right|_{\underline{K}} = \frac{d\pi_k}{d\underline{K}} \frac{k}{\frac{dk}{d\underline{K}}} = \frac{1}{\eta} h k - \alpha \sigma k > 0 \text{ if } \alpha = 0. \quad (\text{A.63b})$$

Thus, capital firms prefer a stricter standard over a higher capital supply subsidy if and only if $\alpha > 0$. Furthermore, from (3.2), the energy firms' profit develops by:

$$\left. \frac{d\pi_e}{dk} k \right|_{\sigma} = \frac{d\pi_e}{d\sigma} \frac{k}{\frac{dk}{d\sigma}} = \frac{\frac{dp}{d\sigma} \frac{\sigma}{p}}{\frac{dk}{d\sigma} \frac{\sigma}{k}} pE < 0, \quad (\text{A.64a})$$

$$\left. \frac{d\pi_e}{dk} k \right|_{\underline{K}} = \frac{d\pi_e}{d\underline{K}} \frac{k}{\frac{dk}{d\underline{K}}} = \frac{\frac{dp}{d\underline{K}} \frac{\underline{K}}{p}}{\frac{dk}{d\underline{K}} \frac{\underline{K}}{k}} pE < 0. \quad (\text{A.64b})$$

Thus, energy firms prefer a stricter standard over a higher capital supply subsidy if and only if $\underline{K} > K^\circ$ from (A.60). Finally, total welfare develops by

$$\left. \frac{dw}{dk} k \right|_{\sigma} = -(\lambda - \lambda_k) \left[\frac{1}{\eta} h k - \alpha \frac{1 + \frac{dk}{d\sigma} \frac{\sigma}{k}}{\frac{dk}{d\sigma} \frac{\sigma}{k}} \sigma k \right] - (\lambda - \lambda_e) \frac{\frac{dp}{d\underline{K}} \frac{\underline{K}}{p}}{\frac{dk}{d\underline{K}} \frac{\underline{K}}{k}} - \lambda \sigma k, \quad (\text{A.65a})$$

$$\left. \frac{dw}{dk} k \right|_{\underline{K}} = -(\lambda - \lambda_k) \left[\frac{1}{\eta} h k - \alpha \sigma k \right] - (\lambda - \lambda_e) \frac{\frac{dp}{d\underline{K}} \frac{\underline{K}}{p}}{\frac{dk}{d\underline{K}} \frac{\underline{K}}{k}} - \lambda \sigma k - \lambda \frac{h - \frac{\partial B}{\partial \underline{K}}}{\frac{dk}{d\underline{K}} \frac{\underline{K}}{k}} k. \quad (\text{A.65b})$$

Thus, society prefers a higher capital supply subsidy over a stricter standard if $\lambda \geq \lambda_e, \lambda_k$.